Road Operator Use Case Modelling and Analysis

5GAA Automotive Association
Technical Report

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Executive summary

The 5GAA work item BRIDGE aims to determine how Communications Service Providers (CSPs) can support the C-ITS/V2X expectation of Road Operators in the near future to encourage and accelerate the deployment of C-ITS use cases on the road.

Following on from a series of discussions with European Road Operator (RO) strategists, a set of four exemplary C-ITS use cases was identified with a view to understanding what might be required from CSPs to achieve the above-mentioned objective. The four use cases were Local Hazard and Traffic Information, Green-Light Optimal Speed Advisory, Probe Vehicle Data and Maps Data Collection and Sharing for High-Definition Maps. Additionally, a set of possible network requirements was considered, including coverage, active quality of service (QoS) management, low communications latency, high network data throughput capacity, and advanced edge-hosted data processing.

After a qualitative analysis, most of the above requirements were ruled out, except for the potential need for high data throughput capacities in areas of greatest service usage, assuming high penetration of service participation. A key network requirement not ruled out was the need for coverage. To determine the potential need for CSPs to make provisions for high data throughput requirements, each use case was modelled in various scenarios, including worst-case parameters, with results compared to theoretical radio sector data throughput capacity models. Short-range systems are not addressed in this study since available unlicensed C-ITS bandwidth is set by international standards and regulatory bodies.

Modelling showed that all of the use cases can be delivered on existing mobile networks today, assuming network coverage is sufficient for Road Operator requirements, with the greatest potential impact due to the HD Maps use case in the context where a large number of ephemeral objects on the road need to be communicated to service providers. This use case is already in commercial production for selected premium vehicles (e.g. Mercedes EQS and S-Class). HD-map geographic availability for passenger cars is initially maintained on highways. More widespread geographic availability will take some years, following adoption of L3/L4 automated driving and the expansion of operational design domains, where higher penetration of vehicles with high sensitivity on-board sensors will be instrumental for ubiquitous live HD maps.

A key assumption made was that cellular networks would have a different profile compared to short-range systems, leveraging current understanding of features verified and used in commercially deployed systems and the different contexts in which cellular networks would be expected to deliver services. Overall, Road Operators whose areas of responsibility coincide with those where mature 4G networks are deployed – and cover roads sufficiently – can be confident that their existing priority C-ITS data services will be carried appropriately over today’s networks, without the need for active CSP support or network capacity expansion, even taking into account service penetration increasing towards full on-road participation.

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Glossary

AI	Artificial Intelligence
BSM	Basic Safety Message (SAE)
BW	Bandwidth
CAM	Co-operative Awareness Message (ETSI)
CDF	Cumulative Density Function
C-ITS	Co-operative Intelligent Transport System
CO2	Carbon Dioxide (greenhouse gas)
CPM	Co-operative Perception Message (ETSI)
CSP	Communications Service Provider
DENM	Distributed Environment Notification Message (ETSI)
DL	Downlink
ETSI	European Telecommunications Standards Institute
GLOSA	Green Light Optimal Speed Advisory
GNSS	Global Navigation Satellite System
HD Maps	Use Case: Data Collection and Sharing for High-Definition Maps
HMI	Human-Machine Interface
I2N2V	V2X Mode: Infrastructure to Network to Vehicle
I2V	V2X Mode: Infrastructure to Vehicle
ITS	Intelligent Transport Systems
IVIM	In-Vehicle Information Message (ETSI)
LHTI	Use Case: Local Hazard and Traffic Information
Lidar	Laser Imaging, Detection, and Ranging
LTE	Long-Term Evolution (4G radio)
MBB	Mobile Broadband
MEC	Mobile Edge Compute
MNO	Mobile Network Operator
NR	New Radio (5G radio)
OEM	Original Equipment Manufacturer
PVD	Use Case: Probe Vehicle Data
QoS	Quality of Service

RLV	Use Case: Red Light Violation
RO	Road Operator
RSU	Roadside Unit
RTA	Road Transport Authority
SAE	SAE International (formerly Society of Automotive Engineers, USA)
SINR	Signal to Interference Noise Ratio
SNR	Signal to Noise Ratio
SPAT/MAP	Signal Phase and Timing/Map Message (ETSI/SAE)
TLC	Traffic Light Controller
UL	Uplink
UE	User Equipment
V2I	V2X Mode: Vehicle to Infrastructure
V2N2I	V2X mode: vehicle to network to infrastructure
V2X	Vehicle to Everything
VoLTE	Voice-over LTE
VRU	Vulnerable Road User

1. Introduction

BRIDGE brings together stakeholders from within the 5GAA community and the Road Operator/Road Traffic Authority community to advance the development of Digital Roads. BRIDGE seeks to establish how Communications Service Providers and V2X Service Providers could deliver RO priorities. Prior to BRIDGE Task 3, extensive work was carried out in BRIDGE Tasks 1 and 2 to determine the top priorities for Road Operators and Road Traffic Authorities. Interviews were conducted with a range of Road Operators, primarily from Europe, but also with some additional insight into the US Road Operator ecosystem. While most of the ROs were national-level institutions in several European countries, BRIDGE Tasks 1 and 2 also featured interviews with some European regional and municipal RTAs. The output from these interviews was a list of ‘priority’ use cases especially important to Road Operators.

With the list of prioritised RO use cases established in BRIDGE Task 1, BRIDGE Task 3 selected a subset of those which are ‘key’ for the purposes of analysing the service delivery and its impact on mobile networks.

BRIDGE Task 3’s primary objective, then, is to identify ‘CSP Strategies’ required by the prioritised use cases, to enable appropriate service quality. In this report we outline CSP Strategies to enhance mobile services, in two ways. Firstly, Available Strategies to enhance the adoption of Digital Roads, considering broad areas of interest for Road Operators, independent of the specific use cases discussed. Secondly, Targeted Strategies that CSPs could implement to deliver the exemplary use cases included in this study, based on the results of data throughput modelling, where each appropriate strategy, or set of necessary strategies, is mapped to each individual use case.

BRIDGE Task 3 comprises an analysis of requirements, derived from each individual Use Case, that would be needed to deliver a theoretical implementation of each use case. Also included is a high-level V2X data delivery model created to evaluate the impact of delivering the use cases on the cellular network, to understand whether the network capacity impact would be significant. Other requirements for each use case are derived though qualitative analysis. This report presents all the above steps in greater detail according to the following structure.

Section 0 presents the exemplary use cases selected from the longer list of key use cases highlighted by Road Operators and Road Traffic Authorities in BRIDGE Task 1.

Section 0 contains the list of general Available Strategies that could enhance the adoption of Digital Roads but are agnostic of any use case identified in Section 0.

Section 0 comprises a qualitative analysis of the requirements needed to deploy each use case over commercial mobile cellular networks.

Sections 0 and 0 describe the use case and radio sector capacity models respectively, which have been created to determine the impact on cellular network capacity from the data expected to be generated by the implementation of the exemplary Road Operator use cases. Input parameters for the model traffic and road environment models (urban, dense urban, highway) have been set to generate use case data levels in the worst-case scenario, so as to examine the effect on mobile network data throughput, per sector.

When modelling V2X message distribution over mobile networks, we assume two different approaches: ‘Digital Twin’ and ‘Geofenced’. In the former, the V2X Service Provider has real-time knowledge of each vehicle’s location and can provide targeted data to it. In the latter approach, the V2X Service Provider’s knowledge of the position of each vehicle is limited to a defined area rather than a specific position, and so it provides all information pertaining to that specific area. In this study, the CSP’s role is to support the transmission of the data according to the combined requirements of the prioritised use cases and the V2X Service Provider.

Section 0 presents the results of the use case modelling exercise, showing how much data throughput would be required to support each use case in various road environments.

Section 0 is a comparison of the required data throughput from the various use cases against possible radio sector theoretical capacity presented in the form of percentages of the whole sector throughput capacity.

Section 9 provides an analysis of the potential effect of implementing the use cases and the likely strategies that could be deployed to enable appropriate performance over the mobile network under the scenarios described.

Section 10 is an Annex containing further descriptions of the various aspects of the study, including the information sources for the use case models.

2. Key Road Operator/Road Traffic Authority use cases

Road Operator interviews delivered a group of prioritised use cases from which a subset of exemplary 'key' use cases has been derived. Some of the use cases already feature in 5GAA's C-V2X Roadmap. Those which are not are defined in projects outside of 5GAA, e.g. C-ROADS [1]. All use cases have a clear I2V, V2I, I2N2V/V2N2I component, or some other variant thereof. Beyond Road Operator interest, all these use cases have another factor in common – they all feature interactions between vehicles and infrastructure (or systems, e.g. traffic control) where the Road Operators have clear involvement.

2.1. Local Hazard and Traffic Information (LHTI) [2]

Local Hazard and Traffic Information is a use case that seeks to improve driving safety and efficiency for road users by informing them of known hazards in a particular location. Approaching road users receive information about the oncoming hazard, including the type and, if appropriate, the duration of the hazardous event. It is also possible to warn road users of a series of hazardous events.

Only information about known hazardous events are disseminated in this use case, although our modelling section (see Section 5) does include a model for 'unplanned road closure on a highway'. Section 10.6.1 contains information about the list of event types that may be considered 'hazards' according to C-ROADS.

2.2. Data Collection and Sharing for HD Maps (HD Maps) [3]

High-definition (HD) maps are typically used for automated driving purposes to provide a Digital Twin of the road that contributes to predictability and safe operations of vehicles. In this use case, vehicles equipped with sensor technologies (e.g. lidar, radar, video) collect data about their surrounding road environment and share the information obtained with a HD map provider (hosted in the cloud). The HD map provider then conflates and processes the information collected from multiple sources to update the HD map for a fresh and accurate representation of the local road situation. Sources of data include probes, satellite imagery, road operator data, scan-drive sensor data, and increasingly crowd-sourced sensor data (as sensor quality improves towards L3 and L4 automated driving).

It should be noted that highly dynamic information like moving vehicles and Vulnerable Road Users (VRUs) is not included as part of the map updates for this use case. Instead, information-sharing about highly dynamic objects is comprised in the 5GAA use case 'Infrastructure Assisted Environment Perception' [4]. What 5GAA may refer to as 'static' 2D/3D objects, map providers may synonymously refer to as 'virtually permanent' objects.

Following discussions with HERE Technologies, a location information provider that also provides HD maps, it was understood that from their perspective, the type of object information collected by vehicle sensor arrays depends on the HD map layer. Each 'layer' corresponds to a distinct level of information types to represent a local situation. Possible map layers include:

- HD Localisation Layer – Provides highly accurate information of road 'furniture' along the road, providing a reference for precise localisation purposes
- HD Lane Layer – Provides highly accurate information of lane geometry, providing a reference for sensor data perception and ensure the sensed surroundings
- Road Model – Foundational to providing the logic and rules of the road and comprises standard definition content like curvature, slope, etc.

The following figure [5] indicates the type of location information presented in a typical HD map that needs to be continuously maintained with sensor data information:

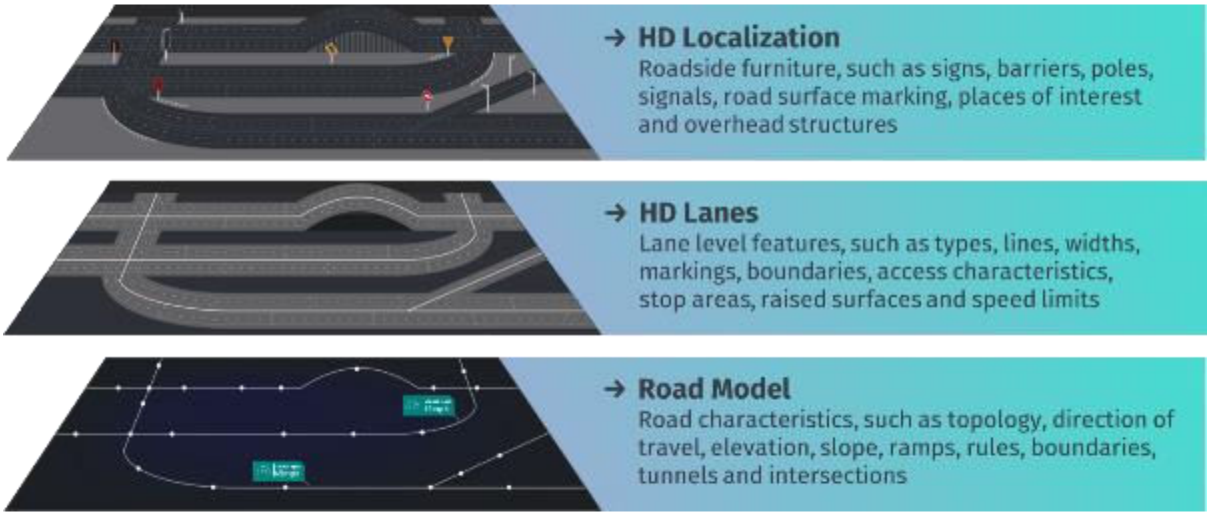

Figure 1 - HD maps layered az1309rchitecture

2.3. Probe Vehicle Data (PVD) [6]

Probe Vehicle Data is a use case that involves the collection of road usage data by the RO or V2X Service Provider. During interviews for this report, Road Operators were unequivocal that the provision of aggregated vehicular speed and directional information combined with position is a desirable information resource to support their operations and strategy.

Modern vehicles know their own speed, direction, position, vehicle type and length. Combining the above data from multiple vehicles gives Road Operators significant visibility over their network, particularly in areas where embedded sensor information is limited. In this use case, vehicles send this data frequently to the V2X Service Provider over the mobile network, and the data is anonymised and processed to create appropriate data sets for Road Operators. The V2X Service Provider can be any entity with access to the appropriate data, including original equipment makers (or a group of OEMs), map-providers, etc. Section 10.6.2 presents the C-ROADS analysis of PVD's potential benefits.

2.4. Green Light Optimal Speed Advisory (GLOSA) [7]

The GLOSA use case provides speed advisory information for road users approaching signalised traffic intersections. The signal phase timing and intersection topography information (SPAT/MAP) is transmitted to vehicles which process the data for the use case. SPAT/MAP information related to a single intersection or combined from multiple intersections may be delivered to vehicles, as decided by the Road Operator.

As a note, the typical scenario for Red Light Violation Warning (RLV) involves a vehicle approaching a traffic intersection at a speed which, if maintained, will pass through a red light. The full use case involves other, nearby vehicles being warned of the impending RLV, in order to avoid collisions at the intersection. RLV can be implemented within the vehicle(s) by combining SPAT/MAP and location (using received Co-operative Awareness Message in the scenario of a remote vehicle predicting another vehicle's RLV), or in the cloud, using the Digital Twin model, where intelligence in the cloud (which has all vehicles' real-time position and velocity) predicts the RLV and communicates the warning to all affected vehicles.

Although GLOSA and Red-Light Violation Warning are two separately recognised use cases, the models here assume that the transmitted messages and service architecture from the perspective of the message transmission are the same. The assumption is that both of these use cases would be processed within the vehicle. In this model, we assume that the vehicle predicts its own RLV and the V2X client warns the driver of the impending violation after calculating the vehicle's speed versus the intersection phase timing. Further warnings to other vehicles are not considered, although under these assumptions the position of the primary vehicle must be communicated to those vehicles in order for them to implement the use case.

3. Available CSP service support strategies

There are several strategies available to Communication Service Providers to enhance the services provided by their communication networks in the event that the requirements of the data delivery service for the use case might exceed the capabilities of the existing network capacity. The definition of a CSP includes any entity involved in providing C-ITS services via a communication link which can be facilitated by both cellular-wide area and short-range communications systems. Entities other than Mobile Network Operators (MNOs) may also be CSPs.

CSPs deliver C-ITS use cases in conjunction with 'V2X Service Providers', by providing a service network that interconnects C-ITS stations (fixed and mobile). CSPs can also be V2X Service Providers (integrated services) or can formally partner with V2X Services Providers. Otherwise, the V2X service will be 'over the top' and dissociated from the CSP's strategies.

A non-exhaustive list of available CSP strategies is presented below, with a brief description of each.

3.1. Network capacity increase

Densification: To increase network capacity with reduced latency, it may be needed to increase the density of base stations, particularly in a road-centric manner to serve traffic volumes. Infrastructure is key to the implementation of this strategy. The expected return on capital invested would need to be considered to assess commercial viability as well as factoring in operational and maintenance costs associated with the required civil works.

Additional spectrum: Deployment of additional and new spectrum bands could be a capacity-increasing strategy. This also means better management of existing spectrum. However, requesting new spectrum is a complex task, potentially requiring navigation of a challenging political environment. It is also costly, factoring in the money spent on spectrum auctions as well as the extra costs associated with the roll-out of new network equipment, especially radio gear compatible only with certain spectrum bands.

3.2. Network coverage expansion

Deployment of existing access technologies including 5G New Radio (5G NR): One available strategy for MNOs to consider is to implement existing radio access systems to expand network coverage. Considerations would likely take into account multiple factors including the cost of deployment, and also the user equipment (UE) profile, i.e. those devices in the field. 5GNR could be rolled out to provide an extra layer of coverage as a complement to existing LTE. However, in scenarios where only 5GNR is implemented, legacy devices will be unable to access certain services so NR should only be considered if the existing LTE network is insufficient to carry the required service or if the customer base is expected to quicky acquire the new UE technology. 5GAA's paper on Network Expansion made it clear that there is unlikely to be any one single recommendation that is appropriate for a variety of territories, since different countries may have different road coverage obligations. The methods to expand rural coverage also varies from one country to another. Depending on the type of service that needs to be delivered, there may also be different considerations for downlink and uplink coverage enhancements.

Traffic-centric, near-ubiquitous road coverage: To extend service availability, road coverage needs to be expanded according to traffic volumes such that it is nearly ubiquitous and is sufficient to cover all roads where there is traffic. This may require more infrastructure, while taking time to deploy. The expected return on capital invested would need to be considered to assess commercial viability as well as factoring in operational and maintenance costs associated with the required civil works.

Additional spectrum: Deployment of additional and new spectrum bands could be another coverage-increasing strategy leading to spectrum with better propagation characteristics. As already noted in the 5GAA C-V2X roadmap report [8], new spectrum below 1GHz would address the requirements and respective strategies.

3.3. Quality of service (QoS)

Enhancing QoS is seen as an essential strategy for optimising the handling of network traffic, particularly under conditions of limited network capacity. Ensuring key services can be delivered with the right traffic prioritisation is an important part of seamless service continuity in congested environments.

3.4. Cross-border C-V2X support

Ensuring good quality network coverage when crossing national borders, reliable handover and roaming agreements would help the delivery of service continuity in cross-border regimes. However, this also requires significant cost as well as time to implement seamless mobility.

3.5. Mobile Edge Computing (MEC)

It is anticipated that Mobile Edge Computing will play a significant role in decreasing the roundtrip latencies between an edge cloud-based application and the road user. MEC brings the application logic closer to the customer (e.g. road user) by operating on the network edge. Thus, increasing the number of MEC sites would improve the density of lower-latency networks to facilitate latency-intolerant service availability for vehicle users. A prerequisite for MEC would be to deploy more decentralised IP Points of Presence to reduce latency. A target for MEC facility improvement would be to ensure that multiple MNOs can seamlessly provide a service with good interoperability. Further, increasing the number of MEC 'peering points' can lower the latency in the essential data transfer pathways that enable customers to access internet-based services.

3.6. Highly available real-time data and low-latency IT interfaces between data exchange elements

Establishing a well-managed data ecosystem could be useful for scenarios where road users would benefit from leveraging high-capacity data networks with sufficiently low latency. Because many road users are attached to a cellular network, CSPs could play a mediator role between various service providers to exchange data which is relevant for safe, efficient, and environmentally-friendly mobility. Establishing efficient data interchange pathways between multiple entities is an area where CSPs could play a role. Currently, silos of data in different ecosystems act as a barrier to data-sharing. CSPs should make the case that there are benefits of sharing data more efficiently, including novel opportunities to commercialise new services. A larger data pool could also be more useful for training AI with enhanced machine-learning. There may still be costs to sharing data, some entities may charge for it.

Data availability and sharing in ITS is mainly relevant in a local context. Because CSPs provide 'compute platforms' in regional data centres, location-based data provision and sharing could be supported by such IT infrastructure.

3.7. Network Slicing

The existence of a bespoke and isolated end-to-end network tailored to the needs of use cases demanding dedicated high QoS is regarded as a strategy to ensure that some use cases (e.g. emergency vehicle approaching, wrong way driver warning, etc.) can be given priority in congested scenarios with high network traffic volumes.

For both QoS/Network Slicing, further analysis still needs to be carried out to determine which Road Operator priorities (use cases) would specifically benefit from these strategies, to understand their potential viability.

3.8. Further analysis on road coverage as a CSP strategy

Historically, communications networks have been built around population centres. However, for C-V2X services, networks will need to be traffic-centric and require new models for network planning. Minimum data rate floors could be set for roads (big and small) in urban, suburban and rural settings. Maximum latency ceilings as well as minimum data rate floors could be used to determine whether road coverage is sufficient. Targets could be set according to predicted traffic density on certain roads, with vehicles ranging from private cars to Heavy Goods Vehicles (HGVs). Targets could also consider weather conditions, such as flood-prone regions in preparation for bad weather. It is noted that in the US, single vehicle failure in isolated regions may be a problem due to sparsely populated, low density areas requiring bespoke coverage considerations in line with the strategic goal of near-ubiquitous road coverage even where traffic volumes are typically low.

Challenges remain regarding the use of traffic infrastructure to support significant increases in road coverage. Public infrastructure re-use should be considered, especially where CSPs and Road Operators can agree to use under-utilised optical fibres [9]. Base station sharing and densification would need to be considered. This requires substantial capital expenditure. There may also be challenges in gaining public acceptance for infrastructure roll-outs deemed to be ideal to meet road users' needs, thus requiring careful thinking around how to organise information campaigns.

4. Requirements for exemplary Road Operator use cases

Requirements inform the capacity and quality of the network needed to support a V2X use case in a commercial, live setting. The network and service entities required to send or receive information, a list of service-level requirements justified by typical user scenarios and the high-level architecture needed for a usage scenario are all important to understand what a use case may generally demand of the network.

The BRIDGE study focuses on what is needed from CSPs to enable the prioritised Road Operator use cases (derived from BRIDGE Task 1) and how these needs can be satisfied. The potential CSP strategies were outlined in the previous section and here we review the use cases to determine whether any of those strategies might be appropriate.

We make the basic assumption that all use cases require network coverage to be deployed in those areas where the service is required. This coverage can be focused on small areas if the use case is location-specific, static and has a low requirement for geographic information dissemination, such as GLOSA/RLV. For this use case, RSUs could be deployed to support specific intersections, whereas for wide-area mobile networks the service will leverage existing mobile network coverage.

In all use case scenarios, we would need to determine whether the data load required to support the service might impact the capacity of the delivery network, which could lead to overall degraded performance, in which case a network capacity strategy would need to be deployed by the CSP. For short-range systems, radio network capacity is determined by available ITS bandwidth (out of scope here), whereas in mobile networks several factors apply (discussed in the previous section).

Similarly, all use cases must be reviewed in terms of the expected latency limits/targets to deliver the V2X information. This depends largely on the nature (or type) of the use case as either critical safety, non-critical safety-related information, or just traffic information/control. Safety-critical is the only use case type that requires the lowest latencies that can be delivered by short-range V2I/V2V systems or similarly V2N with 5G NR. Other use cases can be delivered on 4G commercial mobile networks, albeit ones that are not heavily loaded or close to capacity. Delivery performance for certain classes of data can be managed/guaranteed using active QoS techniques, such as those used today to support VoLTE data, if such requirements are identified.

4.1. Local Hazard and Traffic Information (LHTI)

Local Hazard and Traffic Information applies to a range of message types, including traffic jams, road obstructions and stationary vehicles on highways among others. Some hazard warnings may originate from or be communicated by a Road Operator and others directly from vehicles, according to the C-ROADS definition [10]. BRIDGE is primarily concerned with the delivery of RO services, for which a subset of messages is relevant.

Although a vehicle may encounter different types of hazardous events, the overall flow of information around any particular RO-originated hazard warning will follow a similar path. The key information requirements are the event type, location and the repetition of this information for its duration. Hazard events being communicated by Road Operators must be delivered in a timely fashion to nearby vehicles, but may not necessarily be latency critical. Vehicles can be informed of a static or slow-moving hazard well in advance of reaching its location and it will be presented visually to the driver on approach, by the on-board V2X HMI.

The impact on the network depends on how many concurrent hazards are in a particular vicinity and how many vehicles are to be notified. The highest combination of the two would result in the most significant load on the network.

The service-level requirements for this use case are suitable network coverage (to ensure hazard information can be sent in any location, as well as received in the vicinity of the hazard), and sufficient bandwidth (to accommodate the required data rates). Road hazards tend to be static or slow moving (we do not consider ephemeral hazards such as VRUs in this use case) and thus relatively low repetition rates can serve the arrival of new vehicles within the vicinity needing to be informed.

The definition of vicinity influences the amount of data which needs to be transmitted to receiving vehicles. Furthermore, specific data items to be transmitted can be filtered according to relevance, e.g. driving direction.

4.2. Data Collection and Sharing for HD Maps (HD Maps)

Requirements for this use case will result from the need for vehicles to upload sensed, processed data to the HD map provider's cloud, in reasonable time for the information to be sent to other nearby vehicles via map updates. Requirements depend on the needs and demands of the vehicle OEM and the HD map provider. Depending on the purpose for which the HD map is shared and considering vehicle OEM costs/benefits (freshness vs data acquisition costs), the frequency and granularity of the information might vary. Requirements for HD map updates supporting L2+ driver assistance are likely to be different from supporting L3-L5 automated driving.

The number of objects (and therefore amount of data) that needs to be sent will determine network load. Another aspect that will affect the requirement will be the sensitivity of the vehicles' sensors (i.e. range and accuracy) together with the method(s) deployed in the vehicle client as well as in the service provider backend, to clarify under which conditions re-transmission of sensed objects already included in the HD map is needed (e.g. for more accurate positioning and/or update freshness). The number of vehicles participating in the provision of information to the HD map service in any given area will also affect the demand on the network. There may also be some variation in the number of detectable objects within the environment (i.e. urban, dense urban, highway).

The highest combination of participating vehicles, high on-board sensor capability, and the density of new and detectable objects on the road will place the greatest demand on the network uplink capacity. Presumably, the need for the HD Maps backend to corroborate information sent from vehicles means that low latency is not necessary, but local (in terms of network hosting) deployment of HD Maps server applications could potentially help to balance the amount of data being sent to the map service provider clouds and/or for data files being streamed to the vehicle – if the data level is considered high enough to cause transport performance issues or costs.

From the coverage perspective, detectable objects can be anywhere on the road, so the fullest coverage would be ideal.

4.3. Probe Vehicle Data (PVD)

As described in the previous section, PVD entails vehicles frequently reporting their location and velocity (speed, current heading) for the purposes of compiling road usage statistics for Road Operator business support. Data from all participating vehicles will be aggregated (by road-specific geographical location) and will be processed to reveal information useful for RO business operations and planning (issues of data protection and privacy are out of scope here).

CAM/BSM C-ITS messages, or similar proprietary messages, if OEM-centric solutions are adopted, can be used to enable this use case. In the initial deployment we expect that aggregated data processing will not be in real time, so data will be stored in the cloud and processed according to applicable local data regulatory requirements.

While full coverage is desirable for this use case, road traffic data can be obtained from any roads that have suitable coverage, or a solution could be implemented which transmits stored CAMs when coverage is encountered after a gap. A PVD service could be available for any areas with suitable mobile network or RSU coverage (assuming participating vehicles are also suitably equipped), depending on the capacity effect on the network from this service (and other V2X services).

As outlined above, low latency is not necessary for PVD, since the aggregate data processing function is not real-time. It is also assumed that PVD reports (e.g. CAM, BSM) can be generated at a lower rate than is the rule for V2V use cases, since the granularity (up to 10Hz) is not necessary for road traffic statistical analysis. This assumption is consistent with ongoing commercial deployments such as Talking Traffic in the Netherlands and Mobilidata in Belgium.

4.4. Green Light Optimal Speed Advisory (GLOSA)/Red Light Violation Warning (RLVW)

Signal phase and timing messages contain both the phase and the residual time (in seconds) of the phase or each signal at a junction, and thereby vehicles can compute the approach strategy in advance. Even for active signals that respond to traffic conditions or have variable signal phase durations, adaptations are not expected to occur in sub-second durations. The conclusion is that low latency (tens of milliseconds) is not necessary for the transport of messages to support this use case. Network coverage must be in the vicinity of the intersection which is being signalled and must reach far enough out to give the vehicle/driver enough time to receive the message and apply the approach strategy. However, unlike other discussed use cases, contiguous, city-wide or highway network coverage is not necessary.

Message repetition should be frequent enough to account for vehicles entering the vicinity around the intersection, on the assumption that they may not have previously received the data. In urban areas, where intersections are mostly deployed, vehicle speed is generally limited, so message repetition can reflect this.

Associated MAP messages provide static information on the physical topography of intersections and it may be possible to optimise down the rate of transmission of these messages, based on the distribution approach taken by the V2X Service Provider. The next section introduces different distribution approaches – 'Digital Twin' and 'Geofenced' – which affect the level of data sent to support use cases.

4.5. Conclusions on use case requirements

The four exemplary use cases have been discussed at a high level in terms of the requirements on mobile networks to support them with appropriate quality. All use cases require network connectivity, with GLOSA alone being supportable using connectivity focused on intersection locations. None of the use cases require low latency, such as that offered by short-range or 5G NR. In the downlink use cases (LHTI, GLOSA) the information is not ephemeral and can be sent to vehicles well before it is relevant to them. For the uplink use cases, low latency is not essential.

With the above in mind, we expect that a well-functioning 4G network delivering MBB services should be capable of supporting these uses cases adequately. However, the data load from these use cases (together with other similar ones) in the context of high penetration on the road could prove to be challenging for mobile networks, particularly in areas of high vehicle densities in individual mobile cells or sectors. The use cases must be evaluated from this perspective to see if this is a potential challenge to mobile networks. The next section presents high-level modelling of the use cases to determine the potential levels of data that might arise. The final section will then evaluate these data levels in the context of theoretical mobile network data throughput capacity, to determine whether additional mobile network capacity would be required.

5. Modelling data capacity requirements of exemplary Road Operator use cases

The previous section on requirements identified that none of the Road Operator exemplary use cases demand stringent latency requirements that would require the deployment of QoS, MEC Network Slicing or similar strategies. This may not continue to be true in the future, when more advanced use cases become important to Road Operators, but the immediate requirement simply involves the reliable transmission of use case data plus available network coverage where those use cases apply.

Implementing the Road Operator priority use cases could have some impact on the performance of cellular networks, in terms of additional data capacity required. If some possible impact is expected, then MNOs would need to implement appropriate strategies to accommodate the rise in data traffic. To investigate the network impact, a high-level model to predict data levels generated by each use case has been developed. In parallel, a simplified model of mobile network data capacity is used to determine the impact of each use case. In short, the data generated by each use case, from vehicles within a mobile network radio sector, is compared with the theoretical capacity of that sector and we assess whether there might be an expected resulting impact on network performance. Each use case is modelled in three road environments: urban, dense urban and highway[1]. We then analyse the results to determine the potential for radio sector data capacity impact.

The four main use cases being modelled are:

- Data Collection and Sharing for HD Maps (HD Maps)
- Probe Vehicle Data (PVD)
- Local Hazard and Traffic Information (LHTI)
- Green Light Optimal Speed Advisory (GLOSA)[2]

The above listed use cases are exemplary and were identified as priorities from initial discussions with Road Operators (see Section 1).

When viewed from a data exchange perspective, the first two use cases (HD Maps and PVD) are uplink-centric (V2N2I), in that service information is vehicle-generated and sent from vehicle to network. The latter two use cases (LHTI and GLOSA) are downlink-centric (I2N2V), with vehicles receiving service information from the network.

For all the above use cases, where appropriate, model parameters have been re-used from the Spectrum Needs Study [11].

5.1. Environments, vehicle density and mobile sector coverage

Three main environments for each use case are considered: urban, dense urban, and highway. The rural road environment was not included in this work as it was considered that the low density of vehicles inherent in that environment would not generate any additional challenges for mobile network capability in any of the use cases under consideration.

Each environment has an associated value for vehicle density and a model for mobile network coverage. A variation on the highway environment 'congested highway' was added after consideration of the LHTI use case in terms of an 'unplanned' road closure.

Environment	Dense Urban	Urban	Highway	
			Nominal (avg speed 112kph	Congested (avg speed 48kph)
Mobile network coverage model	3-sector hexagonal	3-sector hexagonal	2-sector linear	2-sector linear
Mobile network sector dimension	Area: 0.072km^2	Area: 0.072km^2	Length: 2.5km	Length: 2.5km
Vehicle density	1000 (per km2)	500 (per km^2)	90 (per km of dual carriageway)	193 (per km of dual carriageway)
Vehicles per sector coverage	36	7.2	225	483

Table 1 - Mobile coverage and vehicle density model input parameters

The radio sector coverage model is described in Section 10.2.

Vehicle densities for urban and dense urban are taken from the Spectrum Needs work item [11]. Vehicle density for highway (nominal and congested) is calculated based on vehicle average speed and recommended inter-vehicle separations. This model is presented in Section 10.1.

[1] GLOSA has not been modelled in the highway environment, since traffic lights are rarely deployed on highways.

[2] The same data can be used for the Red Light Violation use case, so any reference to GLOSA can be read as RLV in this document.

5.2. Information (or message) density parameters

Each use case describes a situation where information is transferred between vehicles and the Road Operator/Service Provider. For the PVD and HD Maps use cases, vehicles send information obtained from the road/vehicle to the Road Operator or HD Maps Service Provider, respectively (uplink). For the LHTI and GLOSA use cases, the RO sends information to the vehicles (downlink).

In PVD, HD Maps, GLOSA and LHTI (for urban environments/congested highway), the amount of data sent depends on 'information density'.

The key elements that make up information density in each use case are listed in the table below.

Use Case	PVD	HD Maps	LHTI	GLOSA
Information density factors	• % participating vehicles • update rate	• % participating vehicles • Vehicle sensor update rate • Number of new detections per vehicle	• Number of roadworks hazards per km2 (Urban areas) • Number of traffic control messages (congested highway)	• Number of traffic signals per km2

Table 2 - Information density factors for service data requirements modelling

5.3. Participation and detectable objects in PVD and HD Maps

For PVD and HD Maps it is likely that not all vehicles will participate in the service since adequate data for road operators (PVD) and HD map service providers (HD Maps) could be provided by a subset of vehicles on the road[3]. It depends on each use case what proportion of vehicles will ultimately be required to support it. The worst case, generating the highest data levels, is 100% participation. Both 50% and 10% participation are also modelled, to better illustrate the effect of reduced participation.

Similarly, for HD Maps, only a subset of the detected on-road artefacts will need to be reported to the service provider, since some objects will have already been reported and, in turn, provided to the vehicle through the HD Maps distribution service (out of scope here). It is likely that static artefacts will be reported very few times, but active (moving) or critical ones, such as VRUs will be reported whenever they are detected.

The 5GAA Spectrum Needs study [11] assumed 50 artefacts per vehicle, which is clearly a worst case. A realistic estimate of object reporting (43 in dense urban scenarios) was modelled. Artefact detection levels of 25 and 10 are also modelled, to represent a more realistic reporting environment.

5.3.1. PVD, HD Maps information density model parameters

Use Case	Probe Vehicle Data	HD Maps Collection and Sharing
Participation	100%, 50%, 10%	100%, 50%, 10%
Information update rate	1Hz	1Hz
# objects detected per vehicle per update	not applicable	43, 25, 10

Table 3 - PVD and HD Maps model input parameters

5.4. GLOSA and LHTI use cases

For the GLOSA and LHTI use case models, the information density represents a level of road operator traffic control activity. Traffic signals at intersections (traffic signals) are modelled for GLOSA, with parameters derived from an example of real city data (signals per km^2), in this case Antwerp in Flanders, Belgium, presented in

[3] In the Real-Time Traffic Information (RTTI) use case, 15-20% penetration delivers a very accurate model of the road traffic condition.

Section 10.3. The number of roadworks instances spread evenly over a city area is modelled for LHTI (urban, dense urban), with parameters also derived from an example of real city data (roadworks per km^2).

Roadworks on highways can be highly distributed across the network, with their activity usually being scheduled for periods when road usage is low. Therefore, for the LHTI use case in the highway environment we model an 'unplanned' road closure, where the highway leading to the incident is congested beyond normal usage (congested highway environment), in the expectation that this scenario will provide a higher stress test to mobile networks.

Traffic lights are relatively rare on highways, so the GLOSA model is not applied to the highway environment.

Environment	Urban	Dense Urban	Highway/Congested Highway
Number of hazards	400	217	1 (single unplanned road closure)
Relevant dimension	126.5 (km2) city area	18.0 (km2) central city area	Not used in this scenario
Information density (number of Hazard Warning messages per km2)	3.16 per km2	12.06 per km2	9 messages (1 DENM/ 8 IVIM) (per road closure event)

Table 4 - Local Hazard and Traffic Information density model parameters (Antwerp city data)

Environment	Dense Urban	Urban	Highway
Traffic signal density	**36 per km2**	**19 per km2**	**not applicable**

Table 5 - GLOSA information density model parameters (Flanders multi-city model)

The analyses that generated the above model parameters are presented in Section 10.3.

5.5. V2X service connectivity architecture model

Connectivity architecture describes how the vehicle (or V2X client, mobile ITS station) is connected with appropriate information by the V2X Service Provider. There are different ways that this can be implemented.

For uplink use cases (PVD and HD Maps) the V2X connectivity architecture is straightforward, since the vehicles must upload their information to the Road Operator or HD Maps service provider, using the V2X service. The connectivity architecture is a simple point-to point (client to server) connection, see below:

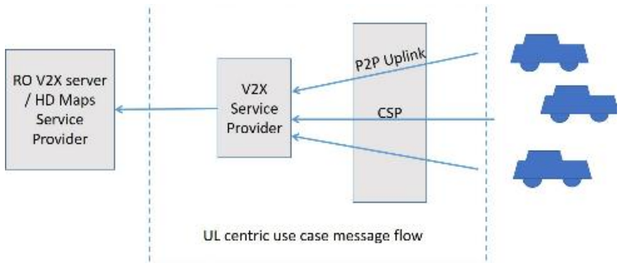

Figure 2 - Uplink simple connectivity architecture

For downlink use cases (LHTI, GLOSA), the method by which the V2X Service Provider identifies the relevant data to send to each vehicle affects the amount of data that will be sent. Again, as a reminder, two generic approaches are included in this study: Digital Twin and Geofenced.

5.5.1. Digital Twin connectivity approach

For the Digital Twin approach, the V2X Service Provider has an accurate, real-time position for each vehicle and sends relevant information only, to each vehicle. One way of providing the Digital Twin with the appropriate position information is for each vehicle to send its CAMs to the V2X Service Provider. The position data load required to support the Digital Twin is likely to be the same as that generated by the Probe Vehicle Data use case, since in each example the vehicle frequently sends CAMs to the V2X Service Provider. Any use cases implemented under the Digital Twin are predicated on the mobile network carrying this data load in the uplink. Section 6.1 shows the data levels associated with the PVD use case. Section 0 shows the comparative data levels with selected radio sector throughput capacity, the highest value is 1.78% of total uplink capacity, in the highway scenario with worst-case selected bandwidth (20Mhz) and SNR (6dB) values, with 100% vehicle participation.

The information sent to each vehicle will originate from a limited area ahead of the vehicle (in our simplified model), determined by the V2X Service Provider. In the study, this area is called the ‘area of relevance’. However, for the highways LHTI model, a ‘length of relevance’ is appropriate, due to the linear nature of highways. In the LHTI highways scenario (unplanned road closure), we assume that the V2X Service Provider will inform all vehicles up to a distance of 10km of the incident (with associated traffic control measures), so the ‘length of relevance’ is 10km.

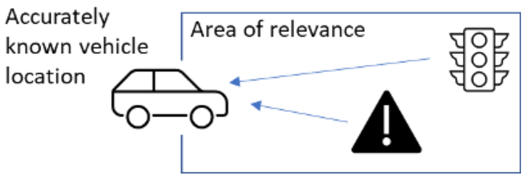

Figure 3 - Digital Twin connectivity approach, showing ‘area of relevance’

5.5.2. Geofenced connectivity approach

For the Geofenced approach, the V2X Service Provider only knows the position of a vehicle within a fixed area. The Road Operator (via the V2X Service Provider) therefore sends all information (GLOSA, LHTI) originating from within that area to the vehicle. The ‘area of relevance’ for geofencing is likely to be larger than the Digital Twin approach, so a larger amount of data will be sent. The method of generating the ‘area of relevance’ for geofencing used in the model is ‘geohashing’ [12, 13], other methods are available.

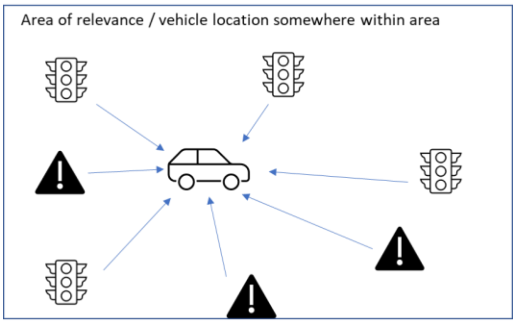

Figure 4 - Geofence V2X connectivity approach, showing ‘area of relevance’

Both Digital Twin and Geofence approaches are stateless for the purposes of the model, so information transmission is repeated with a known frequency by the V2X Service Provider to ensure that vehicles have up-to date information. The two approaches are described in more detail in Section 10.4.

5.6. V2X connectivity model parameters

Both approaches are modelled for each ‘downlink’ use case (LHTI, GLOSA), generating two sets of data requirements results for each. The relevant parameter of the two approaches is the ‘area of relevance’ for each vehicle, presented in the tables below:

5.6.1. Digital Twin ‘area of relevance’

Environment	Urban	Dense Urban	Highway
Area of relevance*	*0.008 km2	*0.008 km2	10km

**Assuming 30m rectangular width, which encompasses the width of an urban road.*
***Only length is considered in the highway environment.*

Table 6 - 'Areas of relevance' in the Digital Twin V2X connectivity model

5.6.2. Geofence 'area of relevance'

Geofencing can be implemented in several different ways. In this model we use geohashing [12, 13] as the approach.

V2X service connectivity architecture	Geohash #7	Geohash #6	Geohash #5
Area of relevance (km2)	0.023	0.744	23.834

Table 7 - Geographic areas described by geohashing lengths 5 to 7, an example of the Geofence V2X connectivity model

The geohash model has multiple results because the user has the flexibility to alter the size of the area for which it reports its approximate position. These values correspond to geohashing lengths of 5 to 7 (longer geohash lengths describe smaller areas). For this study, only the area associated with geohash length 6 is used (1220m x 610m). A larger area of relevance (i.e. geohash length 5) would result in a greater level of data transmission, whereas a smaller one (i.e. geohash length 7) would result in a lower level. A more detailed description of the connectivity approach models is presented in Section 10.4.

5.7. C-ITS message model parameters

For each use case a vehicle will either transmit or receive standardised (ETSI/SAE) V2X information depending on the use case data type and the connectivity architecture. In this model we use ETSI message definitions.

The PVD service is based on the provision of CAMs by vehicles to the V2X Service Provider or Road Operator.

The HD Maps use case does not currently have an open standardised message which could be referenced and used in the model. We have assumed a message size based upon the Co-operative Perception Message (CPM), which is currently in the process of being standardised in ETSI and is estimated to be 1000 bytes in terms of size. The reasoning for this is that the CPM reports position and identification of detected road elements, which is a similar task to providing information for HD maps.

The GLOSA use case requires both SPAT and MAP messages to be transmitted to vehicles. SPAT messages describe potentially dynamic aspects of each signal and must be transmitted frequently (we assume 1Hz in the model). MAP describes static information and so does not need to be transmitted as frequently and can be retained by V2X clients for a long duration.

NB. For the purposes of this analysis, we assume that MAP-related data load is negligible compared with that caused by SPAT delivery, so MAP delivery is not included in the model.

SPAT messages can hold data for a number of phased signals, across multiple traffic light controllers (TLC, or junction). In this model we assume each junction is described with a dedicated SPAT message and that each junction has four individual phased signals (i.e. Manhattan style layout, roads north/south and east/west, including 90 degree cross-carriageway turn manoeuvres), resulting in a SPAT message size of 1600 bytes approximately[4].

The following table illustrates the ETSI C-ITS message types associated with each use case:

[4] Recent industry measurements indicate that real-world SPAT message size is approximately 285 bytes.

Use Case	PVD	HD Maps	LHTI	GLOSA
ETSI C-ITS message type	CAM	CPM	DENM/IVIM	SPAT (4 signals)
Size (bytes)*	100	1000	400	1600
Update Rate (Hz)	1	1	0.1	1

**All values assume compression techniques.*

Table 8 - ETSI C-ITS message data model parameters

6. Exemplary Road Operator use case modelling results

Results of the data load modelling are presented in this section, for each use case and environment combination.

6.1. Probe Vehicle Data (PVD)

Although there are two methods of data collection (automatic and manual) [6], the data exchange pathway in the relevant network impact model need only consider the sharing of processed data by the vehicle to the network (e.g. via CAMs). For this use case, the CAM contains vehicle speed and direction information. CAMs are transmitted by moving vehicles at a regular, fixed frequency. If our model suggests that this is a burden on the network, the frequency of transmitting CAMs could be reduced, but it is more likely that the number of participating vehicles would be reduced.

All reports are sent in real time or sufficiently close to real time (within a few seconds of the detected event). In our model, the following were considered:

- Number of vehicles detecting each event
- Average frequency of update during event
- Average size of CAM

The following table includes the summary of network impact modelling for the PVD use case:

Message size per object	1kByte (8000bits)								
Object reporting rate Hz	1Hz								
Vehicle density per sq_km	90*			500			1000		
Penetration rate %	100	50	10	100	50	10	100	50	10
UL-data per sq_km (Mbit/s)	0.72	0.36	0.072	4	2	0.4	8	4	0.8
Area of serving sector (km2)	2.5			0.072			0.072		
UL data-rate per sq_km (Mbit/s)	1.8	0.9	0.18	0.288	0.144	0.0288	0.576	0.288	0.0576

**This value represents 90 vehicles per km of dual-carriageway, three-lane highway (see Section 10.1)*

Table 9 - PVD uplink data throughput requirements

There are three different contexts for vehicle density (per km^2) ranging from 90 (highway) to 500 (urban) to 1000 (dense urban). There are varying penetration rates measured in terms of percentage of all vehicles per km^2 (100%, 50% and 10%). The final output calculated shows the Uplink Data Rate per sector area in these different contexts.

6.2. Data Collection and Sharing for HD Maps

Similar to PVD, Data Collection and Sharing for HD Maps is an uplink-centric use case focusing on the sharing of processed data from vehicle to network. Sensors, either installed on vehicles (e.g. vehicles equipped with lidar or other HD sensors) or other entities (e.g. roadside equipment such as cameras and other sensors) can collect environmental data around themselves and share the information with a HD map provider (e.g. cloud server). The shared information is processed sensor data (interpreted objects).

The HD map provider analyses the information collected and merges or combines it to build a regional HD map that is dynamically updated and more accurate. This aspect is out of scope here.

Messages used in the HD Maps use case will convey information about a detected object (including object type, position). The number of messages sent per vehicle depends on how many objects are detected.

Object detection also relies partially on prediction so, for example, if the speed and direction of an object is known, the reporting of the objects can be transmitted with a lower periodicity while including the predicted path. The reporting rate is also often configurable. Our model assumes average message sizes, average number of detected objects and vehicle densities in different scenarios (e.g. highway, urban or dense urban). It is worth noting that the real reporting rate and its relationship with the number of objects on the road is more complex. The reporting rate will be lower if a vehicle has already detected an object and sent the information to the map provider, where it is expected that other vehicles will probably not report the same object.

The final output calculated shows the uplink data rate per sector area in these different contexts. Due to reasons discussed above, the number of events reported will likely be a fraction of the number detected for most vehicles. While the assumptions in the Spectrum Needs study [11] were taken as a benchmark, the actual numbers used for reported objects were 10, 25 and 43 for the highway, urban and dense urban scenarios, respectively. These numbers were based on several inputs from 5GAA member companies actively involved in vehicle sensor system deployment that provided estimates on the number of likely reported objects for each corresponding scenario, from which an average was taken to be a good approximation.

The following table summarises the network impact modelling of delivering the Data Collection and Sharing for HD Maps use case:

Reported objects per vehicle	Highway - 10			Urban - 25			Dense Urban - 43		
Message size per object	1kByte (8000bits)								
Object reporting rate Hz	1Hz								
Upload data rate per vehicle (Mbit/s)	0.08			0.2			0.344		
Vehicle density per sq_km	90			500			1000		
Penetration rate %	100	50	10	100	50	10	100	50	10
UL data rate per sq_km (Mbit/s)	7.2	3.6	0.72	100	50	10	344	172	34.4
Area of serving sector (km2)	2.5			0.072			0.072		
UL data rate per sector area (Mbit/s)	18	9	1.8	7.2	3.6	0.72	24.8	12.4	2.5

Table 10 - HD Maps uplink data throughput requirements

6.3. Local Hazard and Traffic Information

The above-presented parameters for vehicle density, Hazard Warning information density, radio coverage and V2X connectivity architecture were used in the model to generate the amount of data load created in situations where Hazard Warnings – planned roadworks in urban and dense urban areas and unplanned road closure on a highway route – are distributed to vehicles. The Geofenced and Digital Twin approaches were applied for all environments and scenarios.

The results are presented in the tables below:

6.3.1. Geofence approach (geohash area value 6, area 1220m x 610m)

Environment	Urban (Antwerp city)	Dense Urban (central Antwerp)	Highway/Congested Highway
Total downlink data per sector	0.027 (Mbit/s per sector)	0.207 (Mbit/s per sector)	1.545 (Mbit/s per sector)

Table 11 - LHTI downlink data throughput requirements (Geofenced)

6.3.2. Digital Twin approach

Environment	Urban (Antwerp city)	Dense Urban (central Antwerp)	Highway/Congested Highway
Total downlink data per sector	0.000 (Mbit/s per sector)	0.002 (Mbit/s per sector)	1.391 (Mbit/s per sector) *

** Includes assumption that V2X Service Providers extend pre-notification distance for vehicles on highways with unplanned road closure scenarios.*

Table 12 - LHTI downlink data throughput requirements (Digital Twin)

6.4. GLOSA

The above-presented parameters for vehicle density, traffic signal density (Flanders multi-city model), radio coverage and V2X connectivity architecture were used in the model to generate the amount of data load created in situations where traffic light phase information (SPAT) is distributed to vehicles in urban areas. The GLOSA use case is not expected to be implemented on highway environments. The Geofenced and Digital Twin approaches were applied for all environments and scenarios.

The results are presented in the tables below:

6.4.1. Geofence approach (geohash area value 6, area 1220m x 610m)

Environment	Urban (Flanders model)	Dense Urban (Flanders model)
Total downlink data per sector	6.4 Mbit/s	24.7 Mbit/s

Table 13 - GLOSA downlink data throughput requirements (Geofenced)

6.4.2. Digital Twin approach

Environment	Urban (Flanders model)	Dense Urban (Flanders model)
Total downlink data per sector	**0.07 Mbit/s**	**0.27Mbit/s**

Table 14 - GLOSA downlink data throughput requirements (Digital Twin)

7. Radio sector capacity model

In this section we apply a simple approach to estimating radio capacity based on Shannon's equation.

Radio sector capacity (bits/second/Hz) can be modelled simply using Shannon's equation relating the mean signal to noise ratio (S/N or SNR) experienced by vehicles and the bandwidth available (B) within the cell/sector.

$$\text{Shannon's Equation: } C = B\log_2 (1 + S/N)$$

7.1. Mean SNR within the radio sector

SNR varies with a large number of factors including physical environment, receiver location, radio frequency (R) equipment and total users. This simple model assumes a mean SNR within the sector. Values of sector capacity resulting from a short range of SNR values, **from 6dB to 8dB,** are considered.

Section 10.5 presents published supporting information for the selection of the above range of mean SNRs for the radio sector capacity model.

7.2. Available bandwidth

For the available bandwidth in sectors, we make an assumption that only 4G bands are used, enabling a frequency re-use of 1 across the radio network – so all available bands are radiated in all sectors.

In reality, we expect multiple MNOs will provide V2X services, in active partnership with V2X Service Providers. For the purposes of this model, we assume two separate MNOs which both have the same network coverage and available bandwidth in their networks, and can share the traffic equally between them. Thus, twice the 'per MNO' bandwidth is available everywhere.

Multiple uplink-downlink paired frequency bands can be available. In urban areas, 2G (800/900 & 1800) plus 3G (2100) bands can be available. All of these bands can support urban or highway environments. We assume that each MNO radiates between 1 and 3 of the above bands in each sector. We assume that the bandwidth of each band is 20MHz, so each sector can have a **total bandwidth of 20MHz, 40MHz or 60MHz** depending on the number of bands radiated.

7.3. Sector capacity

The tables below presents theoretical sector throughput capacity in Mbit/s, based on Shannon's equation using a short range of bandwidth and mean SNR input parameters.

		Mean SNR (dB)		
		6	7	8
Sector Bandwidth (MHz)	20	56.1	60.0	63.4
	40	112.3	120.0	126.8
	60	168.4	180.0	190.2

Table 15 - Theoretical sector data throughput capacity (Mbit/s)

The table shows capacity for a single sector, so assuming two independent MNOs are serving the area with the same radio configuration the capacity will be doubled.

	Mean SNR (dB)			
		6	7	8
Sector Bandwidth (MHz)	20	112.2	120.0	126.8
	40	224.6	240.0	253.6
	60	336.8	360.0	380.4

Table 16 - Theoretical sector data throughput capacity for two independent co-existing MNOs (Mbit/s)

In the next section we will compare these values (two MNOs as contained in Table 16) with those that have been derived in the use case models to determine whether or not the deployment of the use cases might have a significant effect on the capacity and operation of the sector.

Section 10.7 shows the full table of values from 2dB to 9dB mean SNR and for available bandwidth range 2MHz to 60MHz.

8. Comparison of the use case required data throughput with theoretical radio sector capacity

This section compares the results of data throughput requirements obtained through use case and data delivery modelling against the theoretical sector data throughput capacity obtained in the simple Shannon model presented above. A percentage of the capacity is the result of each comparison, with a higher percentage leading to a higher potential impact on the loading and performance of the radio sector under analysis.

8.1. Green Light Optimal Speed Advisory (Geofenced and Digital Twin)

The tables below show the data load expected to be required by implementing the GLOSA use case in various road environments and with Digital Twin and Geofenced V2X message distribution approaches employed, as a percentage of radio sector capacity. Radio sector available bandwidth varies from 20MHz to 60Mhz and mean SNR in the sector varies from 6dB to 8dB.

GEOFENCED DATA DELIVERY

BW\SNR	6dB	7dB	8dB
20MHz	5.70%	5.33%	5.05%
40MHz	2.85%	2.67%	2.52%
60MHz	1.90%	1.78%	1.68%

Table 17 - Sector downlink capacity percentage in urban environment (GLOSA Geofence)

BW\SNR	6dB	7dB	8dB
20MHz	21.99%	20.58%	19.47%
40MHz	10.99%	10.29%	9.74%
60MHz	7.33%	6.86%	6.49%

Table 18 - Sector downlink capacity percentage in dense urban environment (GLOSA Geofence)

DIGITAL TWIN DATA DELIVERY

BW\SNR	6dB	7dB	8dB
20MHz	**0.06%**	**0.06%**	**0.05%**
40MHz	**0.03%**	**0.03%**	**0.03%**
60MHz	**0.02%**	**0.02%**	**0.02%**

Table 19 - Sector downlink capacity percentage in urban environment (GLOSA Digital Twin)

BW\SNR	6dB	7dB	8dB
20MHz	**0.24%**	**0.22%**	**0.21%**
40MHz	**0.12%**	**0.11%**	**0.10%**
60MHz	**0.08%**	**0.07%**	**0.07%**

Table 20 - Sector downlink capacity percentage in dense urban environment (GLOSA Digital Twin)

8.2. Local Hazard and Traffic Information (Geofenced and Digital Twin)

The tables below show data load expected to be required by implementing the Local Hazard and Traffic Information use case in various road environments and with Digital Twin and Geofenced V2X message distribution approaches employed, as a percentage of radio sector capacity. Radio sector available bandwidth varies from 20MHz to 60Mhz and mean SNR in the sector varies from 6dB to 8dB.

BW\SNR	6dB	7dB	8dB
20MHz	**0.02%**	**0.02%**	**0.02%**
40MHz	**0.01%**	**0.01%**	**0.01%**
60MHz	**0.01%**	**0.01%**	**0.01%**

Table 21 - Sector downlink capacity percentage in urban environment (LHTI Geofenced)

BW\SNR	6dB	7dB	8dB
20MHz	0.24%	0.22%	0.21%
40MHz	0.12%	0.11%	0.10%
60MHz	0.08%	0.07%	0.07%

Table 22 - Sector capacity downlink percentage in dense urban environment (LHTI Geofenced)

BW\SNR	6dB	7dB	8dB
20MHz	1.38%	1.29%	1.22%
40MHz	0.69%	0.64%	0.61%
60MHz	0.46%	0.43%	0.41%

Table 23 - Sector capacity downlink percentage in congested highway environment (LHTI Geofenced)

BW\SNR	6dB	7dB	8dB
20MHz	0.00%	0.00%	0.00%
40MHz	0.00%	0.00%	0.00%
60MHz	0.00%	0.00%	0.00%

Table 24 - Sector downlink capacity percentage in urban environment (LHTI Digital Twin)

BW\SNR	6dB	7dB	8dB
20MHz	0.00%	0.00%	0.00%
40MHz	0.00%	0.00%	0.00%
60MHz	0.00%	0.00%	0.00%

Table 25 - Sector DOWNLINK capacity percentage in DENSE URBAN Environment (LHTI Digital Twin)

BW\SNR	6dB	7dB	8dB
20MHz	1.24%	1.16%	1.10%
40MHz	0.62%	0.58%	0.55%
60MHz	0.41%	0.39%	0.37%

Table 26 - Sector downlink capacity percentage in congested highway environment (LHTI Digital Twin)

8.3. Probe Vehicle Data (100% participation)

The tables below show data load expected to be required by implementing the Probe Vehicle Data use case in various road environments and with 100% (worst case) participation in the service from vehicles on the road, as a percentage of radio sector capacity. Radio sector available bandwidth is varied from 20MHz to 60Mhz and mean SNR in the sector is varied from 6dB to 8dB.

BW\SNR	6dB	7dB	8dB
20	0.26%	0.24%	0.23%
40	0.13%	0.12%	0.11%
60	0.09%	0.08%	0.08%

Table 27 - Sector uplink capacity percentage in urban environment (PVD 100% participation)

BW\SNR	6dB	7dB	8dB
20	0.51%	0.48%	0.45%
40	0.26%	0.24%	0.23%
60	0.17%	0.16%	0.15%

Table 28 - Sector uplink capacity percentage in dense urban environment (PVD 100% participation)

	6dB	7dB	8dB
20	1.78%	1.67%	1.58%
40	0.89%	0.83%	0.79%
60	0.59%	0.56%	0.53%

Table 29 - Sector uplink capacity percentage in highway environment (PVD 100% participation)

8.4. HD Maps (100% participation and 43 objects per vehicle detected)

The tables below show the data load expected to be required by implementing the Data Collection and Sharing HD Maps use case in various road environments and with participation in the service from vehicles on the road ranging from 10% to 100%. The number of objects uploaded per second from each participating vehicle depends on the road environment: 43 in dense urban; 25 in urban; 10 in highways. The data load is presented as a percentage of radio sector capacity, where radio sector available bandwidth varies from 20MHz to 60Mhz and the mean SNR in the sector varies from 6dB to 8dB.

Urban (UL objects 25 per veh per sec)										
		Penetration: 100%			Penetration: 50%			Penetration: 10%		
		SNR (dB)			SNR (dB)			SNR (dB)		
		6	7	8	6	7	8	6	7	8
BW (MHz)	20	6.41%	6.00%	5.68%	3.21%	3.00%	2.84%	0.64%	0.60%	0.57%
	40	3.21%	3.00%	2.84%	1.60%	1.50%	1.42%	0.32%	0.30%	0.28%
	60	2.14%	2.00%	1.89%	1.07%	1.00%	0.95%	0.21%	0.20%	0.19%

Table 30 - Sector uplink capacity percentage in urban environment (HD Maps, 25 objects uploaded)

Dense Urban (UL objects 43 per veh per sec)										
		Penetration: 100%			Penetration: 50%			Penetration: 10%		
		SNR (dB)			SNR (dB)			SNR (dB)		
		6	7	8	6	7	8	6	7	8
BW (MHz)	20	22.08%	20.67%	19.56%	11.04%	10.33%	9.78%	2.23%	2.08%	1.97%
	40	11.04%	10.33%	9.78%	5.52%	5.17%	4.89%	1.11%	1.04%	0.99%
	60	7.36%	6.89%	6.52%	3.68%	3.44%	3.26%	0.74%	0.69%	0.66%

Table 31 - Sector uplink capacity percentage in dense urban environment (HD Maps, 43 objects uploaded)

Highway (UL objects 10 per veh per sec)										
		Penetration: 100%			Penetration: 50%			Penetration: 10%		
		SNR (dB)			SNR (dB)			SNR (dB)		
		6	7	8	6	7	8	6	7	8
BW (MHz)	20	16.03%	15.00%	14.20%	8.01%	7.50%	7.10%	1.60%	1.50%	1.42%
	40	8.01%	7.50%	7.10%	4.01%	3.75%	3.55%	0.80%	0.75%	0.71%
	60	5.34%	5.00%	4.73%	2.67%	2.50%	2.37%	0.53%	0.50%	0.47%

Table 32 - Sector uplink capacity percentage in highway environment (HD Maps, 10 objects uploaded)

Take the **dense urban scenario** as an example. With 43 objects reported per vehicle per second, at 100% penetration (with all vehicles participating), with a mean SNR value of 6dB and a carrier bandwidth of 20 MHz, the percentage of network capacity utilised = 22.08%. All the values in the tables above can be read thusly.

9. Summary and conclusions

9.1. Exemplary use cases

GLOSA – Some concern with the Digital Twin approach is that it introduces loads in the low percentages, however it is possible that the Geofence area could be reduced from the current 0.744km^2 single tile to multiple smaller tiles (0.023km^2) allowing sufficient distance away from the intersection to receive the appropriate messaging. A more intelligent V2X client would enable this optimisation. GLOSA implemented using Digital Twin does not impact the sector capacity at all.

Local Hazard and Traffic Information – Only the congested highway scenario impacts the least capable sector radio performance (20MHz, 6dB SNR), but no more than 1.4%. This scenario represents the situation where an accident has partially shut down the highway, almost a worst-case situation. Also, radio coverage may be more benign in the more open highway environment.

Probe Vehicle Data – Even with 100% participation the worst scenario is the highway environment when the radio capacity is least. Low participation will be sufficient for simple traffic statistics gathering on highways, however advanced use cases requiring a higher level of PVD participation could be deployed on highways using existing 4G networks, and without impacting existing networks.

Data Collection and Sharing for HD Maps – Has the potential to stress radio networks more than the other use cases. The worst-case example occurs in dense urban areas under 100% service participation when additional load varies from 6.5% (best radio conditions) up to 22% (worst radio conditions). In this road environment, the number of uploaded objects was set at 43 per vehicle per second, but there was no consensus around this number and it is possible that vehicles will report a lower number of on-road objects than that modelled. It is also worth noting that HD Maps use case was designed to support high levels of vehicle autonomy with accurate road data and a service participation approaching 100%; a situation that will not happen for many years. In this timeframe, 5G and even later generations of mobile network could be deployed in urban areas. Impact on the existing pre-5G network at 10% participation ranges from 2.2% (worst radio conditions) down to 0.66%. Other road scenarios show a lower impact.

9.2. Aggregated and future use cases

It appears to be unlikely that the implementation of many V2X I2V use cases on vehicles will impact the mobile networks significantly in the short term, even when only considering today's 4G networks deployed across most urban areas and highways. This is likely because the event-based nature of the use cases means that the data throughput required to deliver the information can be optimised downwards (using Digital Twin, smaller Geofence areas or lower retransmission frequencies).

V2I use cases appear to be onerous to support in terms of higher throughput requirements, since the data carried is vehicle focused and therefore needs more frequent refreshing. However, for event-based V2I use cases (e.g. reporting bad weather, heavy traffic etc.), comparable results would be expected to the Local Hazard and Traffic Information use case, and so would not be expected to impact significantly the existing 4G mobile networks. The impact of HD Maps could point to potential issues with other I2V services that might be required to support higher levels of vehicle autonomy (e.g. offloading sensor analytics to the cloud), although from the perspective of the BRIDGE work item these use cases can be considered to be related to the business operations of the OEMs rather than Road Operators, and so a different analysis would be required in terms of business support by MNOs for potential customers.

10. Annex

10.1. Vehicle density per km of highway nominal operation

- On UK highways the maxim legal speed is 70 mph (112 kph, 31.1m/s) <max_speed>
- The recommended minimum inter-vehicle separation on highways in the UK is measured in terms of time (2 seconds between moving vehicles) <v_sep> = 61.1m
- The average length of a vehicle (UK) is taken as 4.4m <v_length>
- A typical UK highway class road is dual (two) carriageway <#carriageway> and has 3-lanes for each carriageway <#lanes>

NB. In the worst case (maximum vehicle density), all vehicles are assumed to be driving at the maximum legal speed with the minimum recommended inter-vehicle separation.

Using the above values, worst case vehicle density per km of highway is calculated using the following relationship:

Density per km = (#carriageways * # lanes) * 1000/(v_sep + v_length)

resulting in a rounded value of **90 vehicles per km of typical UK highway**.

10.1.1. Density due to congestion after unplanned road closure

After highway incidents, average speed and inter-vehicle distance is reduced. In the road accident example (Section 10.3.1) vehicle highway speeds are reduced to 30mph (48kph). We assume that the 2 second rule for inter-vehicle distance is maintained and so the vehicle density will increase according to the relationship outlined above. Due to the lower speed (48kph), the value of v_sep reduces to 26.7m and the vehicles density increases to **193 vehicles per km of typical UK highway**.

10.2. Mobile network radio sector coverage according to road environment

Network coverage is modelled to determine how many vehicles are served by an individual sector.

Urban and dense urban mobile coverage uses the classic hexagonal cellular model, where each base station radiates three sectors whose coverage areas are described by a hexagon shape. Each sector serves a number of vehicles according to its area and the vehicle density in the served location/environment.

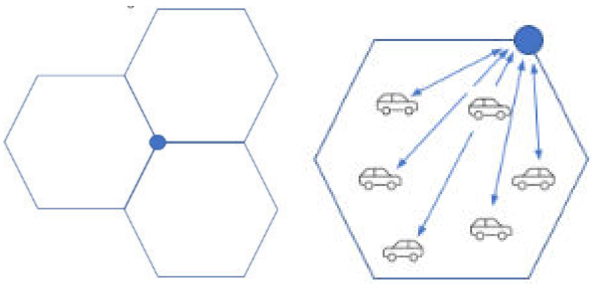

Figure 5 - Urban mobile radio coverage model

From <spectrum needs> the area of urban and dense urban coverage was considered the same, with inter-sector distance (ISD) of 500m at $0.072km^2$.

On highways the coverage is considered to be provided by two sector base stations, with each sector deployed linearly in the direction of the highway.

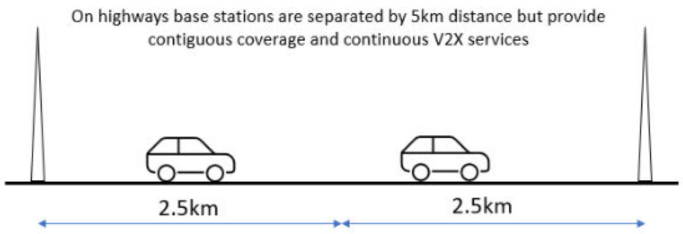

Figure 6 - Highway mobile radio coverage model

Also, from [11] the inter-sector distance between linearly deployed base stations is taken as 5km, thus each sector covers a section of highway with length 2.5km.

10.3. Information density

Information density is a key input to the model being used to determine the impact of V2X use cases on mobile network capacity. It determines, on average, how many road 'events' are relevant to vehicles in the LHTI and GLOSA use cases. This section details how the data to determine the information density was collected and processed.

NB. Accurate and representative data can be obtained by making a large number of density estimates over time and over multiple different municipalities and using statistical analysis on the results. However, due to the time and resource limits of the work item we adopted a pragmatic approach to generating information density which is envisaged to represent a scenario that will be challenging for mobile networks, with respect to real-life situations.

10.3.1. Local Hazard and Traffic Information

URBAN AND DENSE URBAN

For the Local Hazard and Traffic Information use case, a number of online services (web pages) are available which illustrate real-time information on various hazards for certain municipalities. These web pages show maps of the locations of Hazard Warnings together with the number of events. By counting the number of reported hazard warnings and estimating the area of the municipality in which the warnings occur, a rudimentary information density can be calculated.

Inspection of a number of available online resources showed that the municipality of Antwerp appeared to have a significant number of reported roadworks in the central **urban** area, as shown in the diagram below (from https://www.geopunt.be/hinder-in-kaart)). The diagram also shows that the central part of Antwerp had a greater information density than the wider area, so this was measured and used in the model to represent a **dense urban** area in the model for information density.

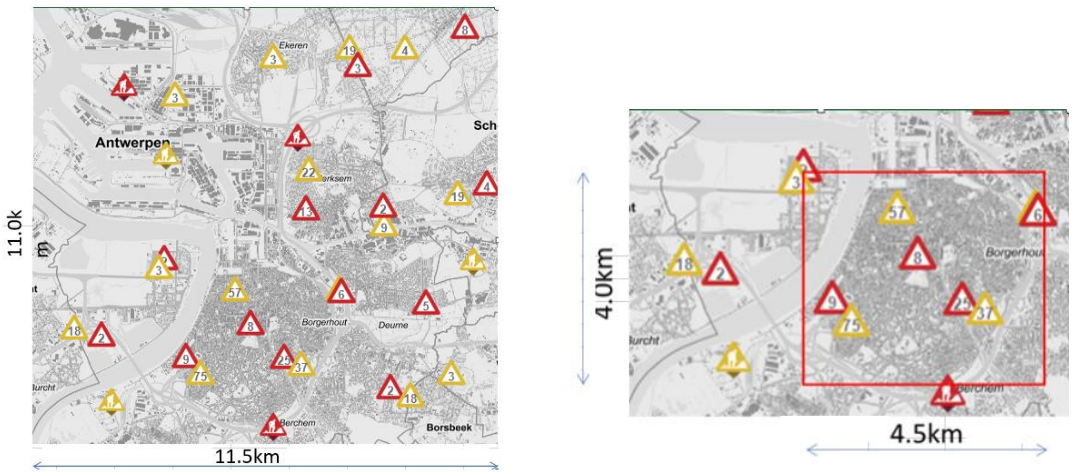

Figure 7 - Roadworks alerts in Antwerp, used for information density model

By visual inspection, the number of reported Hazard Warnings available for reporting to vehicles was determined together with the approximate area over which those warnings occurred, leading to an information density value (hazards per km^2).

NB. This data was collected on 19 July 2022.

HIGHWAYS (CONGESTED DUE TO UNPLANNED ROAD CLOSURE)

The density approach (number of roadworks events/total road length) is not appropriate for highways due to the linear nature of the road layout. In the model below we describe a stretch of dual carriageway, a rural highway on which an unplanned incident has occurred. Each event is communicated to drivers some distance before the start point, which we assume to be10km.

While Roadworks has been assumed to be the main source of LHTI data for urban areas, in the highways model we use the possible reaction to a road accident as the example. The main reason for this is that in reality highway Roadworks and associated carriageway closures are scheduled for the times when highways are least busy (i.e. night-time until the early hours) and so information signalling will be relatively low due to a lack of vehicles.

In this example, an accident during business hours has caused all lanes in a carriageway to be closed. Traffic approaching the incident is congested (vehicles moving slowly, inter-vehicle distance is reduced). The opposite carriageway is operating normally, at maximum speed (although this is not often the case with major incidents). Information sent to vehicles comprises the following:

- 1 x accident event (DENM)
- 3 x speed limit (IVIM)
- 3 x carriageway lane closures (IVIM)
- 2 x slip road (ramp) closure (IVIM)

NB. Highway carriageway lane closures are signalled using IVIM and comprise 'business as usual' messages, replacing regular speed limit information. However, we include these because the incident causes a larger vehicle density to occur and so 'business as usual' signalling will also increase.

In total, nine messages comprise the full information/traffic control provided for the incident.

The model is illustrated below, elements include:

- Three-lane carriageway
- Accident incident notification
- Speed limit advice
- Closed lane advice
- Closed entry slip-road advice

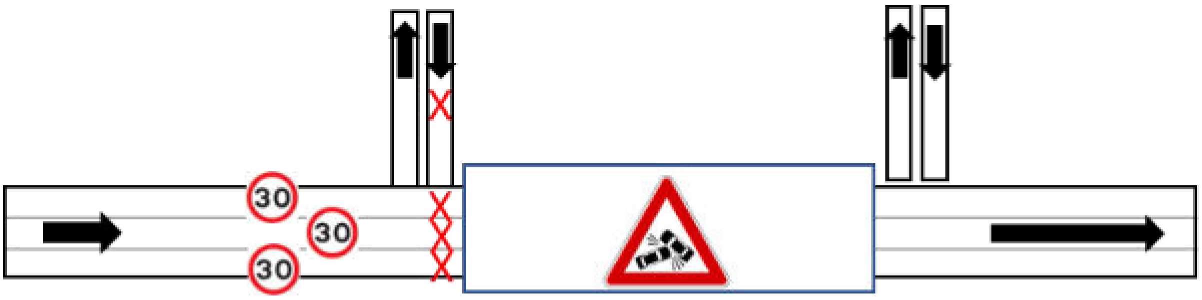

Figure 8 - Highway closure model with LHTI messages

LHTI INFORMATION DENSITY FOR ALL ENVIRONMENTS

Environment	Dense Urban	Urban	Highway
Number of hazards	217	400	1
Relevant dimension	18.0 (km2)	126.5 (km2)	n/a
Information density	12.06 (per km2)	3.16 (per km2)	5 (per road closure event)

Table 33 - Information density parameters for LHTI model

10.3.2. GLOSA

To build this model it is necessary to know the total number of individual traffic signals (i.e. junction signals) that are operated by a municipality and the geographic area of the municipality in which the traffic signals are operated. It is assumed that all signals are virtualised and reported to vehicles as appropriate to the V2X message distribution model.

For this study, a review of cities in Flanders with ten or more Traffic Light Controllers (TLC) was undertaken, registering the total number of traffic signals and estimating the area of each city under study. A graph was produced with the results, allowing the data to be anonymised (as suggested by the data provider).

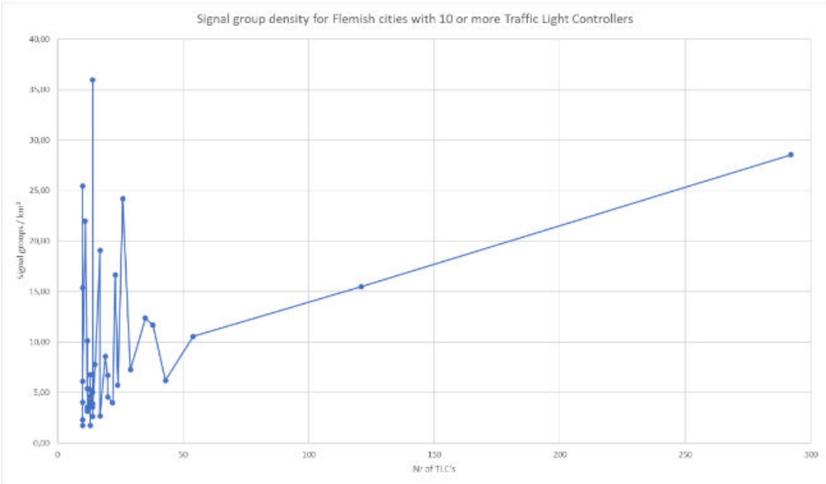

Figure 9 - Traffic signal density in Flanders, input parameter for GLOSA model

In the above table the x-axis represents the number of TLCs in a city and y-axis represents the signal density (#TLCs/city area). From the above we identified values which were then used for the model, see below.

For the dense urban environment, the highest value of 36 signals per km^2 was used ('1' in the graphic below). For the urban environment an average of the three cities with the largest number of signal density ('2': 11, '3': 16, '4': 29 in the graphic below) was used.

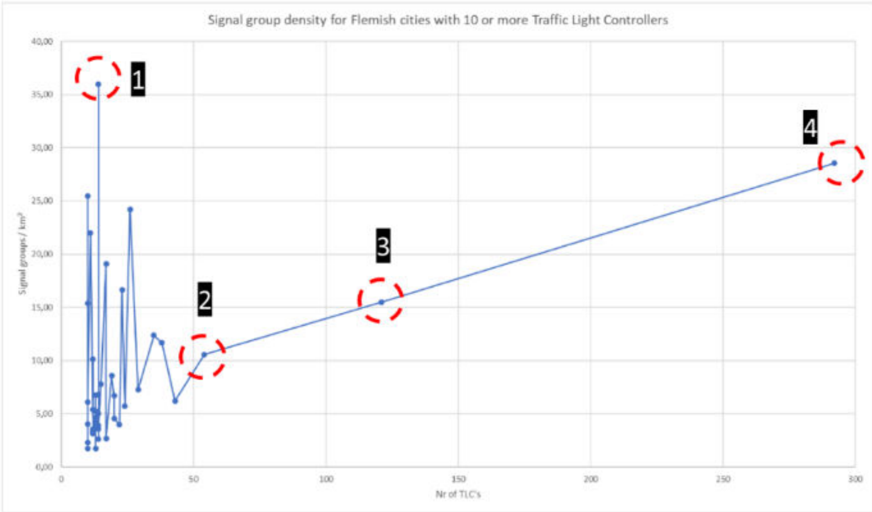

Figure 10 - Selected traffic signal density data points for GLOSA model parameters

FLANDERS MULTI-CITY TRAFFIC SIGNAL DENSITY MODEL RESULTS

Environment	Dense Urban	Urban	Highway
Traffic signal density	36	19 (avg of 11, 16, 29)	not applicable

Table 34 - Selected traffic signal density data points for GLOSA model parameters

10.4. V2X service connectivity architecture

10.4.1. Digital Twin

In the Digital Twin approach, the vehicle/client regularly updates the V2X Service Provider with absolute location and velocity *(velocity data comprises direction and speed)* derived from GNSS data, with repetition frequency f_T. The V2X Service Provider sends all messages from within area A_T (A_T = length l_T x width w_T) immediately ahead of the vehicle, with a specific frequency.

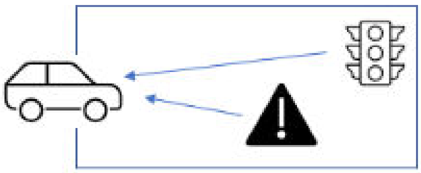

Figure 11 - Information delivered in the Digital Twin V2X connectivity approach

For the purposes of this model the length/dimension of the area of relevance was determined to be related to the maximum legal speed of the vehicle for the environment that it was within and the V2X Service Provider information update period (10 seconds). The width of the area of relevance was set at 30m, a value which is expected to cover urban roads and three-lane, dual carriageway/highway.

Area length = 2 * *(Max speed *refresh period)*

NB. For the highways environment only the length (km) in front of the vehicle is of interest in terms of how many messages will be sent to the vehicles by the V2X Service Provider.

Environment	Urban	Dense Urban	Highway
Max Speed (kph)	48 (30mph)	48 (30mph)	112 (70mph)
Distance travelled during location update period 10sec (m)	133	133	311
Length of V2X Area of Interest	267	267	622
Area of V2X interest*	*0.008 km2	*0.008 km2	**0.622 km

**Assuming 30m width and **Only length is considered in the highway environment*

Table 35 - Digital Twin 'area of interest' according to road environment and speed

10.4.2. Geofence

In the Geofence system, vehicles update the V2X Service Provider by specifying a known, defined area on the surface of the Earth but without specifying its location within the area A_G with a frequency f_G (NB. $F_G << f_T$), which depends on the vehicle selecting one of a range of area sizes defined by the systems (e.g. geohashing) . The V2X Service Provider sends all messages from within area A_G (A_G = length l_G x width w_G) in which the vehicle is contained (NB. $A_G >> A_T$), with a specific frequency.

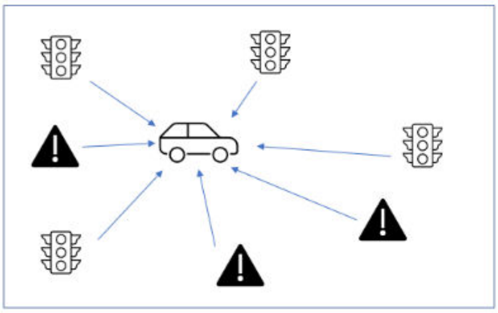

Figure 12 - Information delivered in the Geofence V2X connectivity approach

One well known example of Geofencing is 'geohashing' [12, 13]. In this approach, the client can select the area size according to the number of characters (hash length) that describe the result of the hash process (the client's GNSS location is 'hashed' to determine which area they are currently within). The area size depends on the hash length selected. The hash lengths of 5, 6 and 7 result in the following areas of relevance A_G:

Hash length selected	7	6	5
Area of relevance dimensions (m)	152 x 152	1220 x 610	4882 x 4882
Area of relevance (km2)	0.023	0.744	23.834

Table 36 - Dimensions and size of geohashing areas with hash lengths 5 to 7

In both approaches, the number of messages sent to the vehicle at any time depends on the area (A_G or A_T) and the use-case specific information density (see previous section).

10.5. Mean SNR selection for cell/sector throughput capacity model

The selection of the 6dB to 8dB as the range used to model cell/sector data throughput capacity is supported by the paper by Hasan et al [14] which presents stochastic models of realistic mobile network base station location coverage. Part of the analysis, which compares the realistic approach to hexagonal base station coverage models, calculates the SINR (Signal to Interference Noise Ratio) profile across cells and presents the results in the form of a CDF (cumulative distribution function) diagram. The diagram below, taken from [14] shows the

50% CDF of received SINR in the region around 6dB-11dB, where the most optimistic curve is the hexagonal model for coverage.

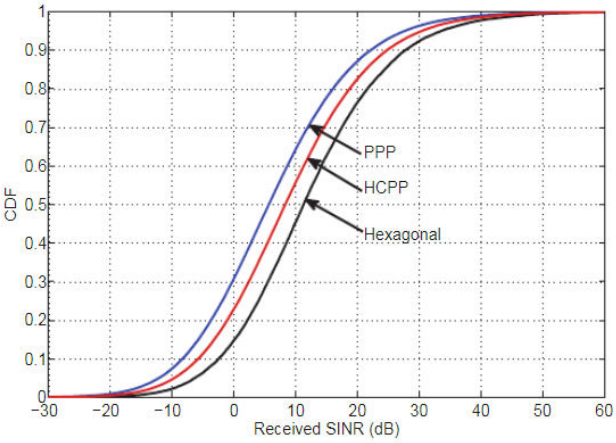

Figure 113 - CDF of received SINR for hexagonal, PPP and HCPPP based cellular networks [14]

10.6. Further use case information

10.6.1. Local Hazard and Traffic Information

According to C-ROADS, the following are all types of hazards about which information might be communicated to vehicle users:

- Traffic Jam Ahead, (HLN-TJA)
- Stationary Vehicle, (HLN-SV)
- Weather Condition Warning, (HLN-WCW)
- Temporarily Slippery Road (I2V), (HLN-TSR)
- Animal or Person on the Road (I2V), (HLN-APR)
- Obstacle on the Road (I2V), (HLN-OR)
- Emergency Vehicle Approaching, (HLN-EVA)
- Emergency Vehicle in Intervention (HLN-EVI)
- Railway Level Crossing, (HLN-RLX)
- Unsecured Blockage of a Road (HLN-UBR)
- Alert Wrong Way Driving (HLN-AWWD)
- Public Transport Vehicle Crossing (HLN-PTVC)
- Public Transport Vehicle at a Stop (HLN-PTVS)

10.6.2. Probe Vehicle Data

The C-ROADS analysis of Probe Vehicle Data outlines its myriad potential benefits:

- Improvement of traffic conditions, network management and event management (improve traffic safety and efficiency)
- Improvement of road network and event impact knowledge
- Improvement of road and weather condition knowledge
- Improvement and evaluation of traffic management strategies

- Faster, more accurate and more efficient event detection and qualification
- A possible cost reduction of the installation/maintenance of detection infrastructure
- Enabling or improving C-ITS services:
  ◦ Location-based provisioning of C-ITS messages/services by service providers
  ◦ (Centralised) collision risk warning or signal violation warning
  ◦ Optimisation of signalised intersections
  ◦ (Dangerous) End of queue warning
  ◦ Extreme weather warning
  ◦ Travel time estimation and information

10.7. Sector capacity model results

	mean SNR (dB)								
Available bandwidh (MHz)	1	2	3	4	5	6	7	8	9
2	2.0	3.2	4.0	4.6	5.2	5.6	6.0	6.3	6.6
4	4.0	6.3	8.0	9.3	10.3	11.2	12.0	12.7	13.3
6	6.0	9.5	12.0	13.9	15.5	16.8	18.0	19.0	19.9
8	8.0	12.7	16.0	18.6	20.7	22.5	24.0	25.4	26.6
10	10.0	15.8	20.0	23.2	25.8	28.1	30.0	31.7	33.2
12	12.0	19.0	24.0	27.9	31.0	33.7	36.0	38.0	39.9
14	14.0	22.2	28.0	32.5	36.2	39.3	42.0	44.4	46.5
16	16.0	25.4	32.0	37.2	41.4	44.9	48.0	50.7	53.2
18	18.0	28.5	36.0	41.8	46.5	50.5	54.0	57.1	59.8
20	20.0	31.7	40.0	46.4	51.7	56.1	60.0	63.4	66.4
22	22.0	34.9	44.0	51.1	56.9	61.8	66.0	69.7	73.1
24	24.0	38.0	48.0	55.7	62.0	67.4	72.0	76.1	79.7
26	26.0	41.2	52.0	60.4	67.2	73.0	78.0	82.4	86.4
28	28.0	44.4	56.0	65.0	72.4	78.6	84.0	88.8	93.0
30	30.0	47.5	60.0	69.7	77.5	84.2	90.0	95.1	99.7
32	32.0	50.7	64.0	74.3	82.7	89.8	96.0	101.4	106.3
34	34.0	53.9	68.0	78.9	87.9	95.5	102.0	107.8	112.9
36	36.0	57.1	72.0	83.6	93.1	101.1	108.0	114.1	119.6
38	38.0	60.2	76.0	88.2	98.2	106.7	114.0	120.5	126.2
40	40.0	63.4	80.0	92.9	103.4	112.3	120.0	126.8	132.9
42	42.0	66.6	84.0	97.5	108.6	117.9	126.0	133.1	139.5
44	44.0	69.7	88.0	102.2	113.7	123.5	132.0	139.5	146.2
46	46.0	72.9	92.0	106.8	118.9	129.1	138.0	145.8	152.8
48	48.0	76.1	96.0	111.5	124.1	134.8	144.0	152.2	159.5
50	50.0	79.2	100.0	116.1	129.2	140.4	150.0	158.5	166.1
52	52.0	82.4	104.0	120.7	134.4	146.0	156.0	164.8	172.7
54	54.0	85.6	108.0	125.4	139.6	151.6	162.0	171.2	179.4
56	56.0	88.8	112.0	130.0	144.8	157.2	168.0	177.5	186.0
58	58.0	91.9	116.0	134.7	149.9	162.8	174.0	183.9	192.7
60	60.0	95.1	120.0	139.3	155.1	168.4	180.0	190.2	199.3

Table 37 - Theoretical radio sector capacity (Shannon's rule) with varying mean SNR and available bandwidth

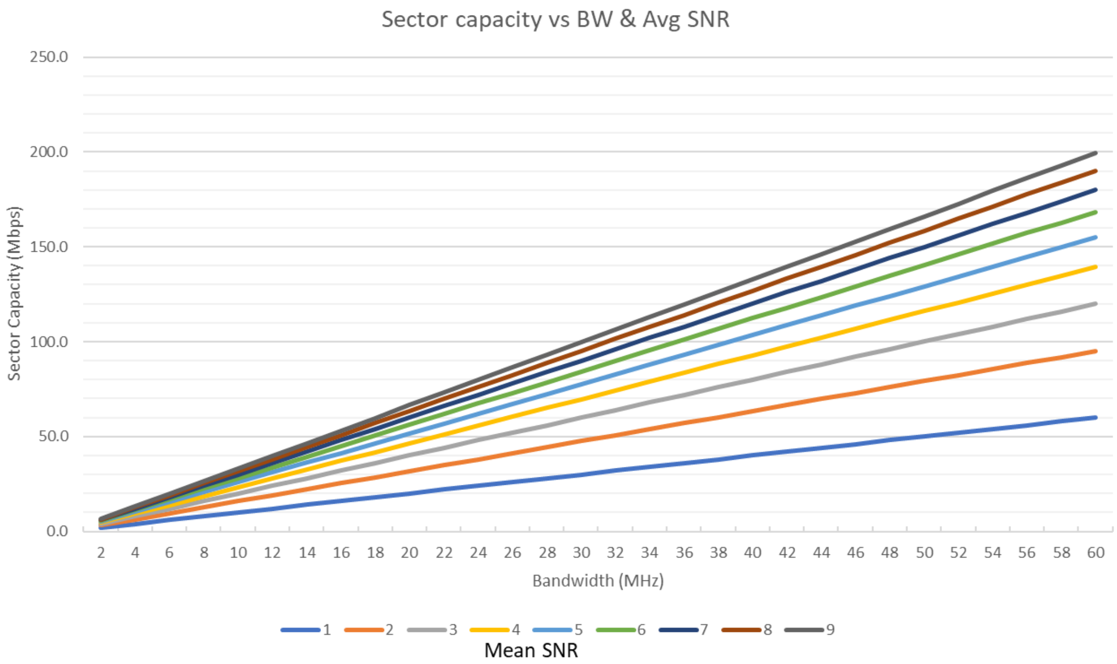

Figure 14 - Graph representation of theoretical radio sector capacity (Shannon's rule) with varying mean SNR and available bandwidth

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