5G for cooperative & connected automated MOBIlity on X-border corridors

D5.3

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ABBREVIATIONS

Abbreviation	Definition
AD	Automated Driving
ADF	Automated Driving Function
ADAS	Advanced Driver Assistance System
AV	Automated vehicle
BEA	Break-even analysis
CACC	Cooperative Adaptive Cruise Control
CAD	Connected and Automated Driving
CAM	Connected and Automated Mobility
CAPEX	Capital expenses
CAV	Connected and Automated Vehicle
CBA	Cost-Benefit Analysis
CBC	Cross Border Corridor
CEA	Cost-Effectiveness Analysis
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
EC	European Commission
IE	Innovation ecosystem
KBDC	Knowledge-Based Dynamic Capabilities
KPI	Key Performance Indicator
MAMCA	Multi-Actor Multi-Criteria Analysis

MEC	Mobile Edge Computing
MNO	Mobile Network Operator
NOX	Nitrogen Oxides
OBU	On-Board Units
ODD	Operational Design Domain
OEM	Original equipment manufacturer
OPEX	Operating expenses
PM2.5	Fine particulate matter, diameter of less than 2,5 micrometers
PM10	Particulate Matter, inhalable particles with diameters 10 micrometers or smaller
QoL	Quality of Life
RSU	Road-Side Unit
SORT	Simple Online and Real-time Tracking
TCO	Total Cost of Ownership
TOR	Take-over Request
TS	Trial Site
TTC	Time To Collision
UCC	Use Case Category
US	User scenario
WMG	Warwick Manufacturing Group
V2I	Vehicle-to-infrastructure
VOC	Volatile organic compounds
VRU	Vulnerable Road User

WTT	Well-To-Tank
X-border	Cross-border

EXECUTIVE SUMMARY

Context

This is deliverable D5.3 "Report on impact assessment and cost-benefit analysis" of the 5G-MOBIX project. The main objective of the deliverable is to report results of the impact assessment and cost-benefit analysis of the 5G enabled connected and automated mobility (CAM) solutions and services in cross-border contexts, developed and trialled in the project. The assessment has been conducted from the societal perspective.

Relevance to service continuity in cross-border context

The quality of life impact assessment studied likely impact mechanisms of the 5G-MOBIX user scenarios in cross-border contexts on traffic safety, efficiency, the environment and personal mobility, in comparison with the baseline of connected automated driving with connectivity issues. The methodology builds on the impact assessment framework for Automated Driving (AD) developed by the Trilateral Working Group on Automation in Road Transportation. By using the framework it was possible to systematically analyse the potential impacts, by identifying the relevant impact mechanisms and pathways, through which impacts on quality of life aspects can be expected. The most important mechanisms of 5G in the 5G-MOBIX user scenarios are the following:

- Vehicle operations: Speed behaviour, interaction with other vehicles and VRUs
    - Mechanism: 5G connectivity in Lane merge and automated overtaking can affect interaction with other vehicles and VRUs, which affects vehicle operations and through that safety, efficiency and environment
- Driving quality: Frequency of harsh braking
    - Mechanism: 5G connectivity affects the frequency of harsh braking, which affects driving quality and through that safety, efficiency and environment
- Quality of travel: Traveling reliability (reliability of travel time)
    - Mechanism: Automated shuttle remote driving across borders improves reliability of travel time and through that quality of travel and potentially travel behaviour

The cost-benefit analysis sought to answer whether it is cost beneficial, from a societal welfare perspective, to invest specifically in 5G infrastructure that enables CAM services at border crossing areas compared to the existing communications infrastructure. The analysis was conducted for five European cross-border corridors: Spain – Portugal (ES-PT), Greece – Turkey (GR-TR), Germany – Netherlands (DE-NL), Finland – Norway (FI-NO), Spain – France (ES-FR). The analysis considered overall benefits, in terms of safety, travel time and environment, potentially resulting from deployment and adoption of 5G enabled CAM services.

Summary of the main results and conclusions

The break-even cost-benefit analysis produced an estimation of the required reduction in costs related to negative externalities (accidents, CO_2 emissions and delays) to offset the investments needed to enable cross-border 5G for CAM solutions. For busy cross border corridors, Spain-Portugal (ES-PT), Germany-the

Netherlands (DE-NL), Spain-France (ES-FR), the levels of the needed benefits to offset the investment costs seem possible to be achieved in all scenarios, ranging between 0.44% and 1.99% (assuming equal reductions in all included externalities). Due to the low traffic volumes at the Finland-Norway (FI-NO) corridor, break-even is unlikely to be achieved only through reduced costs related to negative externalities. Investments at the Greece-Turkey (GR-TR) corridor are not likely to be offset by the societal benefits included in this analysis, but benefits to trade and logistics might be expected, and those could thus offset the costs. The results of the business models analysis and assessment of monetary benefits for fleet owners at GR-TR corridor are presented in the deliverable D6.6 [1].

The quality of life impact assessment analysed the expected impacts of 5G and implications of those for traffic safety, efficiency, the environment and personal mobility. The enhanced anticipation of the traffic situation ahead, enabled by 5G, can lead to avoiding takeovers and jerky trajectories, keeping a more constant speed, avoid harsh brakings and avoid conflicts with other road users. The user scenario with most effects is *Lane merge and automated overtaking* because those situations were quite frequent also in cross-border context.

When assessing impacts of changes to the traffic system such as the addition of connected and automated vehicles to traffic, it is important to take into account both the potential effectiveness of the measure, as well as the prevalence of the situation addressed by the measure in the transport system or network. The prevalence of cross-border situations in the broader context (i.e. a large traffic network) is small, as the share of vehicle kilometres travelled in cross-border situations is low compared to the whole road network. However, from the subjective view of specific travellers or drivers crossing borders regularly, the perceived benefits may be highly relevant. As an example of local benefits for specific user groups, but also benefitting society, time savings and CO_2 emission reductions that may be achieved through the *Assisted border-crossing* use case were estimated. By improving the border crossing processes, an average time saving of 15 minutes per truck could be achieved, resulting in the overall time saving of 48.500 hours per year. The enhanced border crossing can also lead to decrease in idling time, when the drivers or vehicles receive instructions in advance, and queue build up is decreased. Assuming that all trucks arriving at the border over a year could save on average 5 minutes of idling time, 63 tons of CO_2 per year could be saved.

A new methodology for assessing a traffic safety parameter, Time To Collision (TTC), with video analytics, was developed and tested in the project. The methodology may in future enhance availability of quantitative information about safety parameters in trials and real traffic situations. However, tens or preferably hundreds of situations should be captured, analysed and combined with vehicle and network data in the analysis, in order to gain statistically significant results, thus serving as quantitative input data to impact assessment. The experiments with the methodology in 5G-MOBIX revealed challenges in video capturing during the night and brough out the necessity of careful planning and organisation of the set-up in real environment. These fed into the further development of the methodology.

1. INTRODUCTION

1.1. 5G-MOBIX concept and approach

5G-MOBIX showcased the usefulness of 5G technology for advanced Connected and Automated Mobility (CAM) technology use cases and validate the viability of the technology to bring automated driving to the next level of vehicle automation (SAE L4 and above). To do this, 5G-MOBIX has demonstrated the potential of different 5G features on real European roads and highways, creating and using sustainable business models to develop 5G corridors. 5G-MOBIX has also utilized and upgraded existing key assets (infrastructure, vehicles, components) allowing the smooth operation and co-existence of 5G within a heterogeneous environment comprised of multiple incumbent technologies as ITS-G5 and C-V2X.

5G-MOBIX executed a series of CAM trials along cross-border (x-border) and trial sites using 5G technological innovations to qualify the 5G infrastructure and evaluated its benefits in the CAM context. The Project has also defined deployment scenarios and identified and responded to standardisation and spectrum gaps.

Firstly, 5G-MOBIX has defined critical scenarios requiring advanced connectivity provided by 5G, and the associated features to enable selected advanced CAM use cases. The matching of these advanced CAM use cases and the expected benefits of 5G was tested during trials on 5G corridors in different EU countries as well as in Turkey, China, and South Korea.

The trials also allowed 5G-MOBIX to conduct technical evaluations. Impact assessment was conducted for the defined advanced CAM use cases. Cost-benefit analysis was conducted based on the deployment scenarios. As a result of these evaluations and international consultations with the public and industry stakeholders, 5G-MOBIX identified new business opportunities for the 5G enabled CAM and proposed recommendations and options for its deployment.

Through its findings on technical requirements and operational conditions, 5G-MOBIX is expected to actively contribute to standardisation and spectrum allocation activities.

1.2. Purpose of the deliverable

This deliverable reports on the findings and conclusions of the assessment of societal impacts and the cost-benefit analysis of the 5G-MOBIX project and provides insight into the potential impacts of 5G cross-border solutions in the context of CAM for the economy and society. Although the wide-scale deployment of the solutions demonstrated in the project will still be years ahead, it is essential to assess economic aspects and potential large scale societal impacts in early phases and to share information on various aspects to be taken into consideration during the phases towards deployment. The deliverable also presents gaps in available information and uncertainties that have been identified during the assessment of Quality of Life impacts

and cost-benefit analysis. These findings can also be used to inform the preparation of future projects and the development of methodologies for impact assessment.

This deliverable aims to highlight the viewpoints on 5G technology for advanced Connected and Automated Mobility (CAM) use cases that are relevant for the whole society. The factors affecting more directly businesses of individual companies, their partners and customers are analysed and discussed in the 5G-MOBIX deliverable D6.6 [1].

Section 2 briefly introduces the overall scope of the study and the four distinct perspectives applied in the impact assessment and cost-benefit analysis. Additionally, the overarching limitations of the study are discussed.

Section 3 presents a new methodology to evaluate the traffic safety performance of the vehicles, using video analytics of overhead aerial footage. The section also presents the results of the tests with the methodology carried out at the ES-PT cross-border corridor.

Section 4 first describes the methodology for assessing the potential impacts of the 5G for CAM solutions in cross-border contexts on mode choice, travel time and throughput, traffic safety, and emissions. The mapping of potential impact mechanisms and their pathways for the use cases is presented, and the section then proceeds to present the assessment results.

Section 5 presents an example of quantified potential impacts of the user story *Extended sensors for assisted border crossing* at the Greece-Turkey cross-border corridor. This user story was excluded from the QoL assessment as its relevance from the traffic system perspective was considered low. However, the potential time savings at border crossing are estimated, shifting, in this case, the focus on another type of significant impact, namely, the benefit of the transport and logistics industry but also for the border control authorities.

Section 6 introduces the review results on costs and benefits and then proceeds to describe the refined methodology for the cost-benefit analysis, and break-even analysis. Results of the analysis are presented for four deployment scenarios.

Section 7 presents the results of the assessment of advances supporting future business design. The section also discusses factors affecting success of an innovation ecosystem, based on increasing number of literatures on the topic. Identified advances and issues feeding into evolvement of innovation ecosystem supporting 5G for CAM vision are presented.

Section 8 summarises the key results and conclusions for D5.3 and discusses the learnings for future projects.

1.3. Intended audience

The deliverable D5.3 is a public deliverable, and it is addressed to any interested reader. It aims at providing information and viewpoints of the societal impacts and cost-benefit for the wide range of 5G-CAM stakeholders, such as telecom industry, automotive industry, other vertical industries, policy makers, governmental bodies and research organisations.

Interested readers may also refer to:

- D5.2 - Report on technical evaluation [2]
- D5.4 - Report on user acceptance [3]
- D6.5 - Final report on the deployment options for 5G technologies for CAM [4]
- D6.6 - Final report on the business models for cross border 5G deployment enabling CAM [1]

These documents are available for free download on the 5G-MOBIX website (https://www.5g-mobix.com/resources/deliverables).

2. OVERALL APPROACH

2.1. Scope of the impact evaluation

The purpose of 5G-MOBIX Impact Assessment was to assess the impacts of seamless service provisioning across borders from a socio-economic perspective.

The main objectives set for the impact assessment task in D5.1 [5] were:

- Explore how 5G-MOBIX systems can affect quality of life, in terms of personal mobility, traffic efficiency, traffic safety and the environment.
- Evaluate how the cooperation between the stakeholders and trial sites in the project has contributed to the development of new innovations and business models and (future) deployment of solutions.
- Assess the costs and benefits of 5G-MOBIX solutions from the perspectives of the society.

The set of metrics for Quality of Life and Business impact assessment, initially presented in D5.1 [5], is presented in Table 1. The Quality of Life focused on assessing impacts of 5G-MOBIX enabled solutions in cross-border contexts on mode choice, travel time and throughput, traffic safety and emissions. The concept of quality of life in this report refers **to impacts on the transport system level, benefitting society on a large scale**. Thus, benefits for an individual, a specific limited target group (such as truck drivers or tourists) or a company are not focused on in the assessment, unless these can be seen to induce wide-spread impacts in the society. The work on business models, including analyses of value propositions for target customers, is reported in the deliverable D6.6 [1].

The cost-benefit analysis presented in this report explored, whether it is cost beneficial, **from a societal welfare perspective**, to invest in 5G infrastructure that enables CAM services at border crossing areas. Furthermore, assessment of a set of factors reflecting stakeholders' preparedness to build upon emerging business opportunities were included in the study.

Table 1: The metrics for Quality of Life and Business Impact Assessment

Class		ID	Description
Quality of Life	Personal mobility	IA- M1.1	Mode choice
	Traffic efficiency	IA-M2.1	Travel time and throughput
	Traffic safety	IA-M3.1	Traffic safety
	Environment	IA-M4.1	Emissions
Business	Customer need	IA-M5.1	Strategic fit of 5G-MOBIX solutions (CAM services across borders and in context of national roaming)

	Costs	IA-M6.1	5G infrastructure building costs
		IA-M6.2	Capital expenses
		IA-M6.3	Operating costs
	Revenues	IA-M7.1	Revenue streams
	Progress towards commercial deployment	IA-M8.1	Number of mature solutions entering the market
		IA-M8.2	Development of capabilities within the ecosystem
		IA-M8.3	Evolution of business models

This study comprised of four different perspectives and approaches to impact assessment and cost-benefit analysis, namely:

- Development of a new methodology for assessing traffic safety indicators by capturing images from an overhead perspective and analysing them with the help of machine learning algorithms,
- Assessment of impacts on Quality of Life (QoL), building on the impact assessment framework for Automated Driving (AD) developed by the Trilateral Working Group on Automation in Road Transport, and the method applied in the AUTOPILOT project [6],
- Cost-Benefit Analysis (CBA) studying the costs and benefits from a societal perspective that are expected to occur as a result of the infrastructure investments enabling border crossing connected automated mobility, and
- Assessment of metrics and factors reflecting advances in collaborative innovation activities and feeding into future business development

The methodologies, analysed scenarios and assumptions related to each of the above-mentioned focus area are described separately in the relevant sections presenting the approach and results of each focus area in detail. It is worth noting, that the approaches of the quality of life impact assessment and cost-benefit analysis differ in the scope: QoL focused specifically on the 5G-MOBIX use cases (basing on the descriptions developed in T5.4) and the impact of 5G on CAM, whereas the cost-benefit has a wider perspective on costs and benefits of 5G for border crossing CAM without specified use cases[1]. Furthermore, the CBA built on the information and assumptions determined in the 5G-MOBIX Deployment study (summarised in 5G-MOBIX deliverable D6.5 [4]) and conducted also the cost-benefit analysis for the five European cross-border corridors, ES-PT, GR-TR, DE-NL, ES-FR and FI-NO, covered by the Deployment study.

[1] Business model analyses for the use cases can be found in the deliverable D6.6 [1]

2.2. Limitations of the study

A major part of the solutions and services discussed in this study are yet to be deployed in realistic conditions, even in limited contexts. Consequently, there is a lack of empirical information on the behaviour of AVs (beyond SAE level 2), and on AVs enhanced with connectivity realised by any means. Due to the nature of cross-border trialling of the project, having a limited geographical scale and scope, the project could not contribute with such data. As an example, credible empirical information about the impacts on traffic efficiency and environment would require a test setting with a realistic number of vehicles (potentially including also manually driven vehicles), a wide area, and people with mobility needs for that context. 5G-MOBIX trials were mostly carried out in closed roads and the number of vehicles used in the trials ranged between one and four.

The methodologies and the level of detail in the defined metrics had to be notably adjusted during the work, compared to the original plans, to overcome the limited availability of empirical data. Gradually it became evident that little, if any, data are available to be used for credible assessment of quantitative impacts. Numerous estimations and assumptions were necessary to be made to be able to conduct the analyses. These are presented and justified in the deliverable.

Challenges were also faced in assessing costs (both CAPEX and OPEX) related to the solutions and services, due to confidentiality of such data but also, because the services and the related business models are only emerging and there is a lack of sufficient information about their design and components. Uncertainties in future economic estimates may also be increased by the current geopolitical and macroeconomic environment.

Work on business models and stakeholder perspectives was conducted in T6.2; the results are available in D6.6 [1].. The Multi-Actor Multi-Criteria Analysis (MAMCA), initially outlined in D5.1 as an approach for the assessment in 5G-MOBIX, has been developed to facilitate the decision-making process by the different stakeholders, by providing an overview of the advantages and disadvantages of the different options. In 5G-MOBIX, the MAMCA methodology as such was not suitable for supporting the economic analysis, since distinct alternatives, such as different types of business models, to be presented to the stakeholders are only emerging at this stage.

3. TRAFFIC SAFETY EVALUATION WITH VIDEO ANALYTICS – TIME TO COLLISION ASSESSMENT

3.1. Introduction to Traffic Safety Evaluation with Video Analytics

Traffic Safety is a long-lasting concern of populations, municipalities and governments, as traffic incidents cause great disruption to people's lives, in a community, whilst creating damaging effects for the local economies. Throughout the last decades many efforts have been put forward to reduce traffic incidents and increase awareness for traffic safety. The introduction of new technologies such as 5G communications and CAM presents an opportunity to further develop tools to increase sensitivity to traffic scenarios in which safety is at risk.

Traditional evaluation of traffic safety has often been carried out by observation of events from a ground level perspective. Our approach aims at broadening the available methods of observing traffic scenarios, capturing images from an overhead perspective using aerial vehicles, namely drones, equipped with cameras, providing a larger field of view for posterior processing and analysis. This approach allows for the evaluation of changes in vehicles' speeds and trajectories, and consequential distances between them. The method can be used to assess safety conditions of new solutions that are aimed at improving traffic flow, efficiency, and safety. The methodology has been developed in the project and it was tested in 5G-MOBIX trials at the ES-PT CBC trial site. Details related to the ES-PT CBC trials can be found in D4.3 [7].

The development of this method is aiming at its potential adoption by road operators and other traffic management entities for evaluation and providing insights towards improving safety in their traffic solutions. The usage of the method in this project is scoped at evaluating the safety conditions, in which an AV using 5G-connected CAM technologies is subjecting nearby connected vehicles, during the execution of the ES-PT CBC trials in two use cases: Lane Merge and Overtaking, with the purpose of assessing the impact on safety of a successful network handover or in the case of a network failure.

3.2. Traffic safety evaluation parameters

To gauge the effects of a 5G network in the operation of an automated vehicle, specifically in terms of the safety conditions it is subjecting its surroundings, analysis of time-based safety indicators is the most reliable way to assert that safety thresholds are respected throughout any network event occurrence.

Traffic safety evaluations encompass many analysis tools and indicators to provide insights and different perspectives into traffic scenarios, for the specific use cases (Lane Merge and Overtaking) and development of the video analytics algorithm. In this project only the Time To Collision (TTC) indicator was implemented for evaluation, since it is regarded as the most relevant and important safety indicator. TTC is determined between two vehicles moving in conflicting trajectories, headed for a collision in the case no avoidance action is taken.

The threshold for this indicator has been researched and studied by many scholars which have provided reference values for many situations, as seen in Table 2 below [8]. Due to expected evasive and preventive manoeuvres by the AV a low level of conflict of the trajectories of the vehicles was desired. Consequently, threshold values were selected accordingly, from Table 2, and defined at a minimum of 1.6 seconds with a desirable value above 2 seconds.

Table 2: Minimum and desirable TTC threshold values indicated by different studies, as summarized in [8].

Authors	Minimum	Desirable	Condition
Van der Horst	1	1.5	Approaches at intersections
Sayed et al.	1.6	2.0	Low level of conflict
Hogema and Janssen	-	3.5	Non-supported drivers
Hogema and Janssen	-	2.6	Supported drivers
Vogel	1	2	Approaches at intersections
Meng and Qu	2	4	Urban Road Tunnel (rear end crash)
Huang et al.	-	1.6	Signalized intersection
Sayed et al.	-	3	Signalized intersection
AASHTO; Farahet al. & Hegeman	-	3	For 2-lane rural roads

3.3. Dataset treatment and training the model

The video analytics process applied in this project involves computer vision algorithms based on machine learning technologies. The method used is leveraging on open source object detection model called YOLOv4 [9], which has been developed for improved speed and accuracy over its previous iterations. It comprises a single Neuron that must be trained and refined according to the specific outputs expected. The scope of information implied in object detection comes in the form of presence detection, location, and type of object or classification, represented in the footage as bounding boxes surrounding the detected objects.

Figure 1: Object Detection and tracking of vehicles in ES-PT corridor trials

Training footage is fundamental to obtain the best possible results, most application of computer vision applied to traffic scenarios are accomplished at eyelevel/vehicle body mounting level and give a very personalised perspective of events, construed by one specific beholder. Our proposed solution involves the usage of drones hovering the action field recording aerial footage at an overhead perspective capturing the unfolding events and reactions of multiple intervenient actors in a conflict prone area.

The implication of an aerial overhead perspective is that it causes new challenges for the model trained with conventional datasets (eyelevel with three-dimensional depth), due to drone flight height, scale and excessive background interference. Therefore, a special aerial image dataset was needed to train the model.

To improve the results, some alterations to the model were implemented including: Two extra detection layers, to increase sensitivity to both large and small objects; Neural network resolution was increased to 608x608 to increase detection precision.

Inherent instability of drone hovering overhead is always present, as slight as it might be with increasingly advanced drone technology. Consequently, some video pre-processing is required to prepare the dataset to be further processed by the YOLO algorithm in proper condition.

While YOLO is responsible for Object Detection frame by frame, object tracking is as important for the purpose of this project, so to accomplish this, the Simple Online and Real-time Tracking (SORT) algorithm was used, and it focuses on frame-to-frame prediction and association for multiple object tracking. The inclusion of such an algorithm allows our solution to track each instance of objects detected (be it vehicle or pedestrian) by YOLO, assigning it an ID and storing all related information frame by frame. This enables further analysis of the data gathered and calculation of various derived measurements and results pertaining to the behaviour observed between all actors of the traffic scenario.

3.4. Results of the traffic safety evaluation with video analytics

The following section showcases the collected data, provided by the video analytics algorithm, which allows us to analyse tendencies and gain a more comprehensive understanding of how automated driving technologies can cope with human driving behaviours and maintain safety conditions. The video data collection was conducted at the Spain-Portugal cross-border corridor. During the evaluation of video analytics results, some test cases produced more consistent outcomes than others, with clear tendencies and unexpected events occurring. Unfortunately, only a limited number of video clips from the total amount of video footage collected from the trial site had sufficient image quality and met the required conditions for the video analytics model to perform and provide results for the entirety of the manoeuvre. For the overtaking manoeuvre only 3 out of 12 obtained videos qualified for video analysis, and for the lane merge only 4 out of 21 obtained videos qualified for video analysis. This was due to insufficient road illumination and uncertainty of handover location in many of the test runs. Consequently, this analysis was unable to provide enough data to generate statistically significant results. Nevertheless, the video footage that

qualified for the video analysis model, was processed and provided the results described in the following subsections.

3.5. Overtaking

The overtaking manoeuver was performed during the trials described in D4.3 [7] at the ES-PT CBC, on a closed road. There were three (3) cars inline on the lane to the right, with the Leading Car (Connected) in front, followed by the AV in the middle. These two cars are the subjects for the analysis. The third vehicle on the back was a regular car. A fourth vehicle was alongside the AV, on the lane to the left, blocking the space for the overtaking until the place where the handover is expected. When they got to the handover point the fourth car on the lane to the left accelerated and moved away from the scene freeing space for the AV to overtake the leading vehicle by moving to the left lane and accelerating. The TTC indicator was only assessed for the AV and the leading vehicle. The settings and conditions under test on the 5G network on which our video data was captured is ES-PT-2.6 (TCS-ES-PT-AdDr-Overtaking-06) presented in D5.2 Appendix A section 1.3.6. Test ES-PT-2.6 is meant to test S1 handover with S10 interface in Home Routed in ES and PT NSA networks while performing the overtaking in the border between two PLMNs based on the Upload/Download data flows between the vehicles and the home MEC using a PT SIM.

During the overtaking manoeuvre, many tests showcased a tendency for the vehicles to slow down slightly before the execution of the manoeuvre, while the following car (automated) retained its relative speed against the leading car, contributing to an increase in TTC, which is positive safety wise.

In two of the tests, test A and test B, a decrease in speed since the start of the manoeuvre can be identified (see Figure 2 and Figure 4), coinciding with very low data point values for the TTC indicator, near its recommended minimum thresholds of 1,6 to 2 seconds. A plateau of TTC values can be observed during the middle of the manoeuvre, between the 15.5 to 18 seconds mark in test A (Figure 3) and between the 10 to 11.5 seconds mark in test B (Figure 5), where the automated vehicle retains its relative speed against the leading vehicle. A rise in TTC values can be seen at the end of the manoeuvre, 18 to 20 seconds mark in test A and 11.5 to 18 seconds mark in test B, coinciding with the fact that the automated vehicle is changing its course, by moving to the left lane, shifting its trajectory away from the leading vehicle and improving its TTC safety value as a result.

Test A video is available via the following link: https://youtu.be/Lv2Fwxr8r7g and test B video via the following link: https://youtu.be/l-019KD78og.

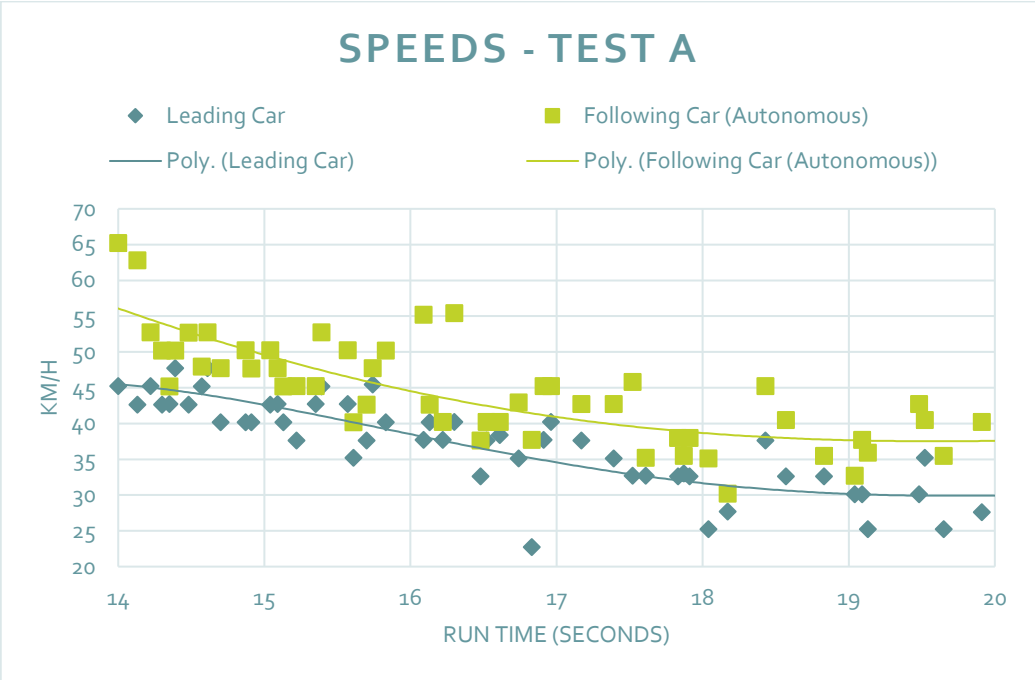


Figure 2: Plot of vehicles' speed during execution of test A

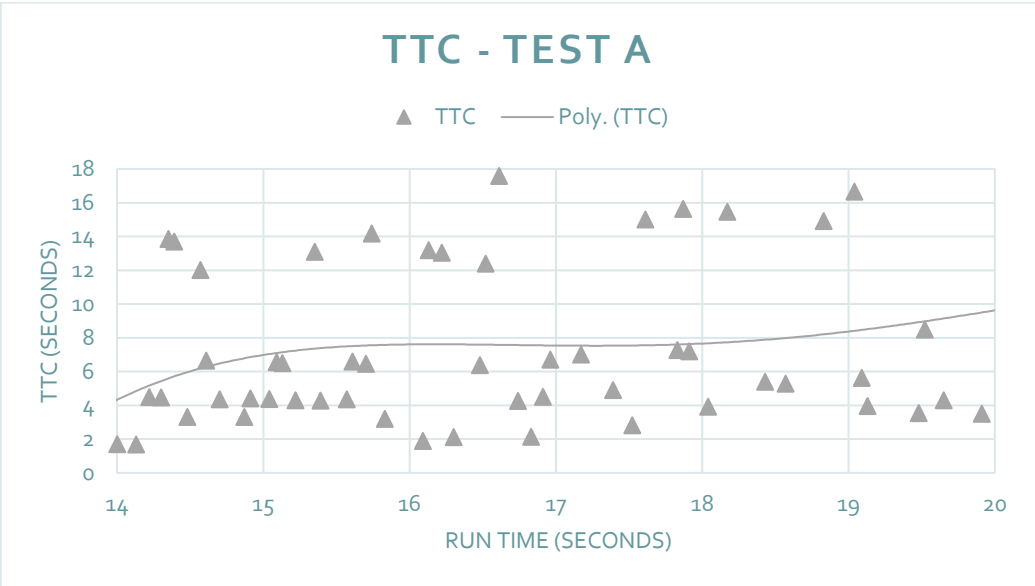


Figure 3: Plot of Time To Collision (TTC) during execution of test A

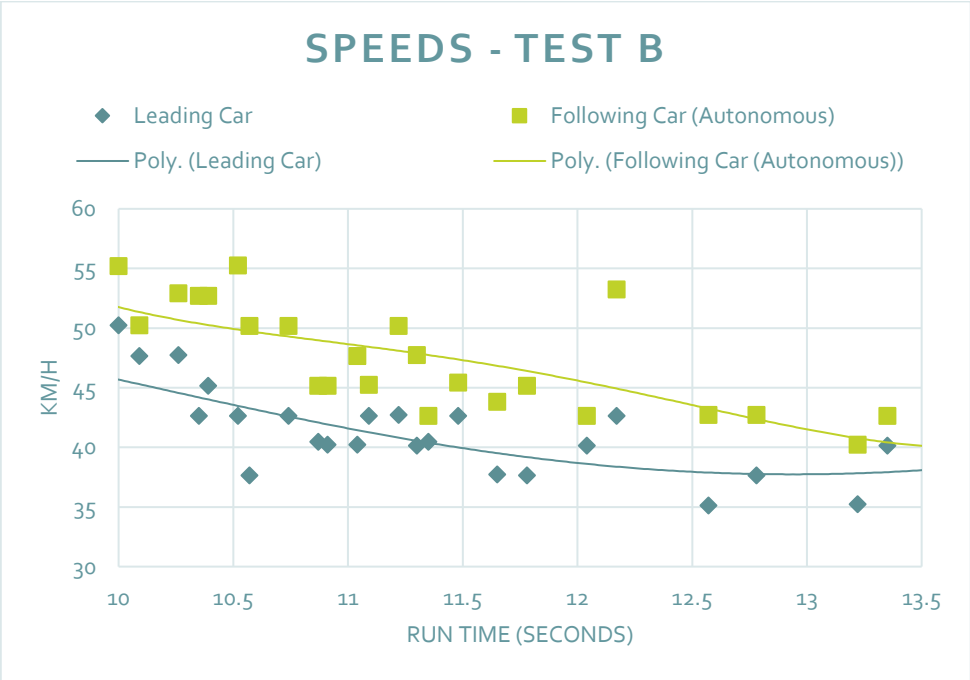


Figure 4: Plot of vehicles' speed during execution of test B

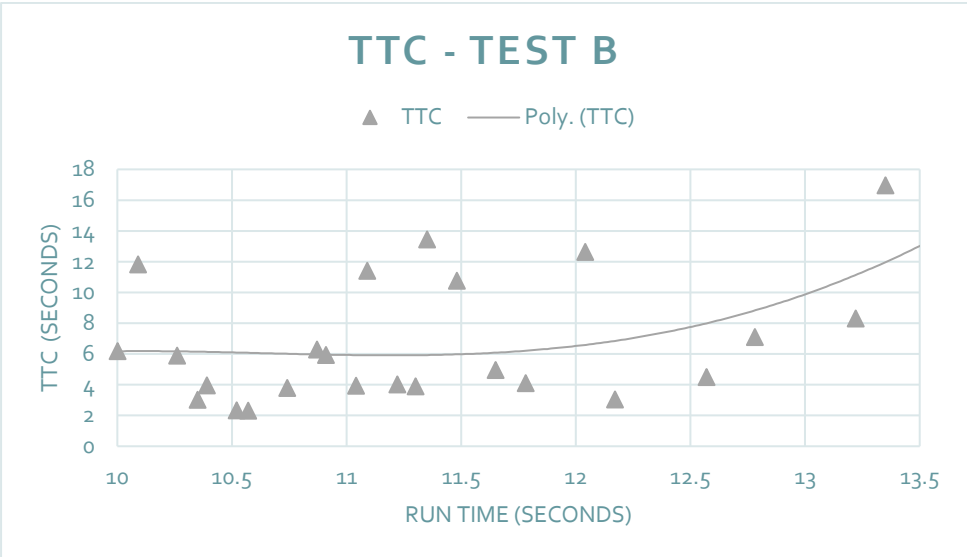


Figure 5: Plot of Time To Collision (TTC) during execution of test B

Network activity during the trials was unstable, which resulted in missing network data, regarding handovers or failed handover attempts and respective timestamps, for some test runs. Test A had a successful handover before the start of the manoeuvre, while the vehicles were not in the frame of the video for test A. Test B did not perform a handover and no network data was retrieved, possibly by a failed connection to the 5G network by the vehicles at the start. Despite this fact, tests A and B demonstrate

similar tendencies supporting the assumption that failures in the 5G network during cross border events have very limited interference with vehicle safety, if any at all.

The following test C deviated from the pattern observed in other test runs. Initially vehicles started the manoeuvre with lower speeds, but with significantly less distance between them, resulting in a TTC value below safety thresholds of 1.18 and 1.34 seconds to collision, between the 6.5 to 7.5 seconds mark, in the graph in Figure 7 below. This condition was solved by the automated vehicle changing lanes and separating their previously conflicting trajectories, while the leading vehicle increased its relative speed.

Test C video is available via the following link: https://youtu.be/o_MGqAOhdA8.

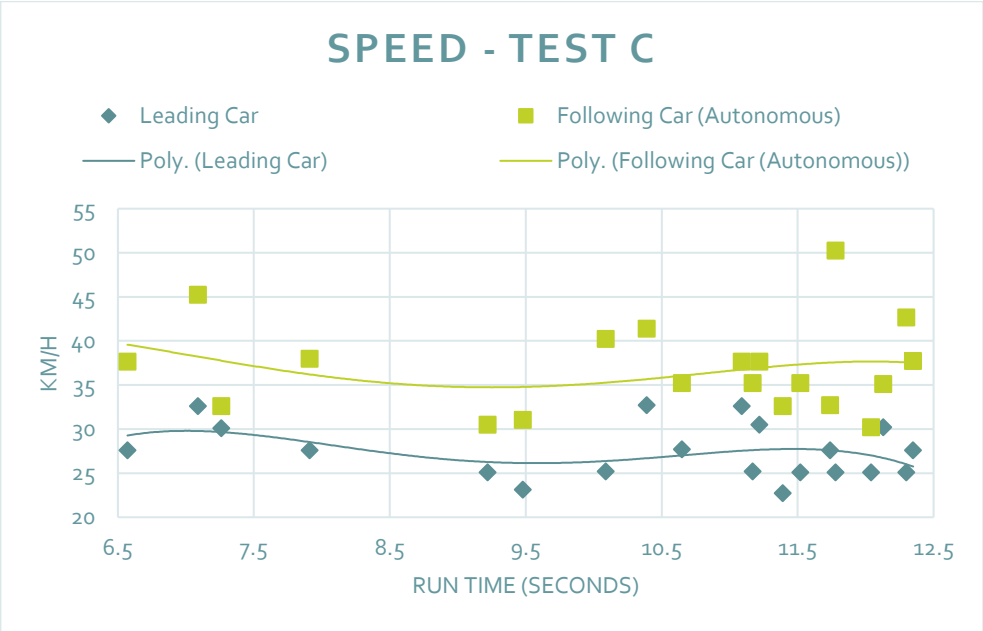


Figure 6: Plot of vehicles' speed during execution of test C

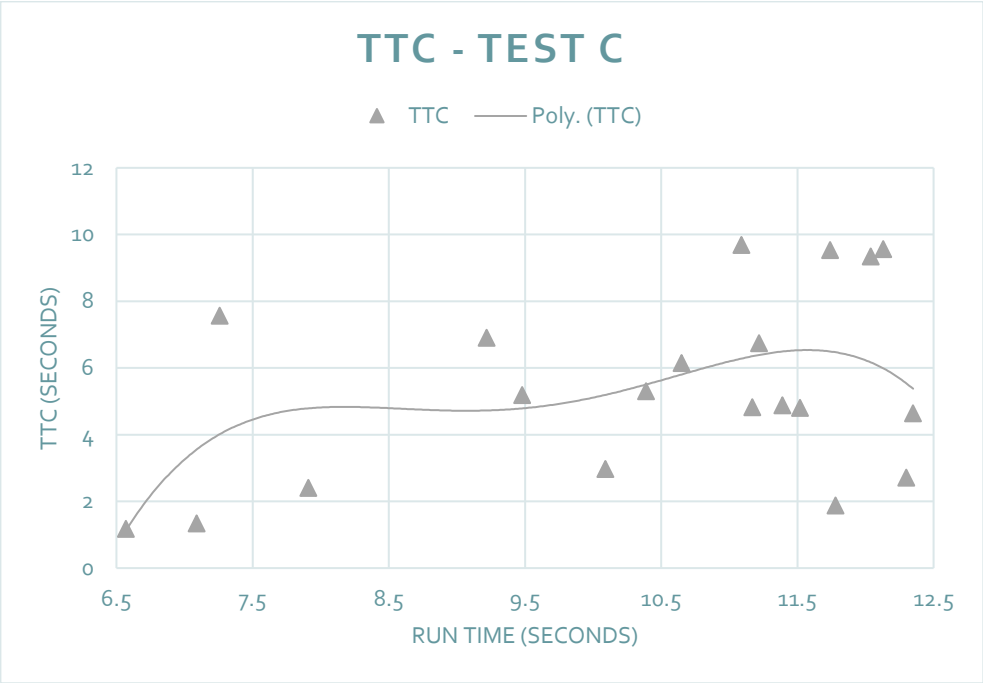


Figure 7: Plot of Time To Collision (TTC) during execution of test C

3.6. Lane Merge

The lane merge manoeuvre involves two connected vehicles and one AV. The AV arrives at the lane merge area after both connected cars have passed it and then performs the manoeuvre, merging into the same lane with both previous cars. For this use case, a significant portion of tests did not imply situations in which the lane merge manoeuvre was performed in an unsafe condition, measurable by the TTC indicator. To be specific, the TTC indicator is only available in situations in which the following car is moving faster than the leading car and both cars have conflicting trajectories. This means most evaluated tests verified the automated lane merging was performed in good safety conditions. The settings and conditions under test on the 5G network on which our video data was captured is ES-PT-1.2 (TCS-ES-PT-AdDr-LaneMerge-02) for test D and ES-PT-1.4 (TCS-ES-PT-AdDr-LaneMerge-04) for tests E and F. ES-PT-1.2 and ES-PT-1.4 are meant to test the release and redirect using the S10 interface in Home Routed in ES and PT NSA network while performing the lane merge in the border based on the Upload/Download data flows between the vehicles and the ES MEC using the ES SIM for ES-PT-1.2 and PT SIM ES-PT-1.4.

<u>During the Lane Merge:</u>

From the 21.6 to 22.8 second mark of Test D in Figure 8, the AV represented in green in the below graphs performed the lane merge in which its speed was greater than the leading car, creating a condition of possible safety risk, although only for a small period of time. Despite this, due to the low speeds involved and enough distance between vehicles practiced by the AV, the TTC values only came close to its threshold

in one instance after the 22 second mark, while most of the values recorded where above the 4 seconds level, as plotted in the graph in Figure 9.

Test D video is available via the following link: https://youtu.be/bWpE_fbiyhI.

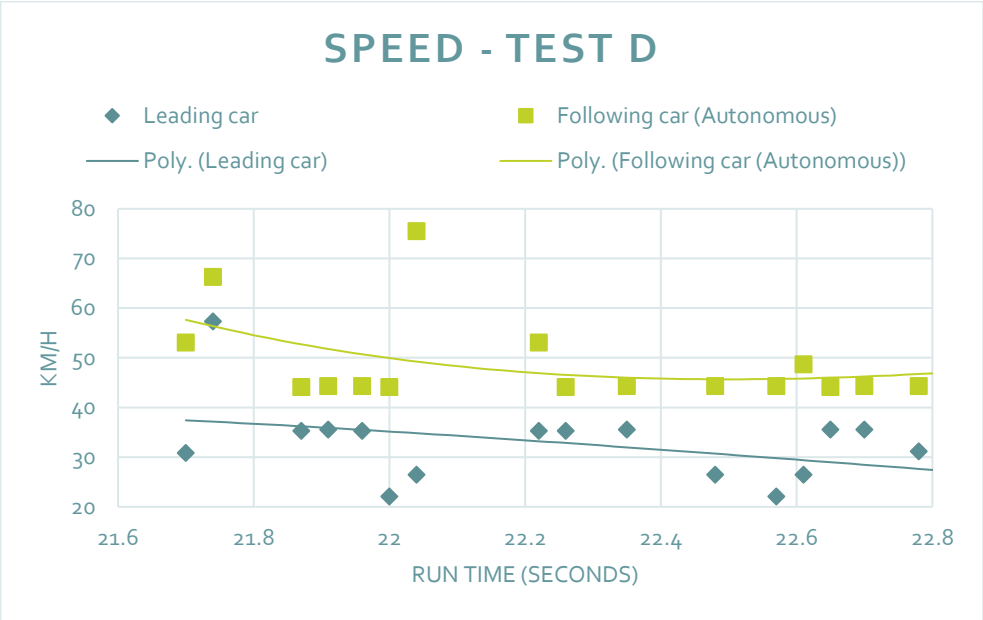


Figure 8: Plot of vehicles' speed during execution of test D

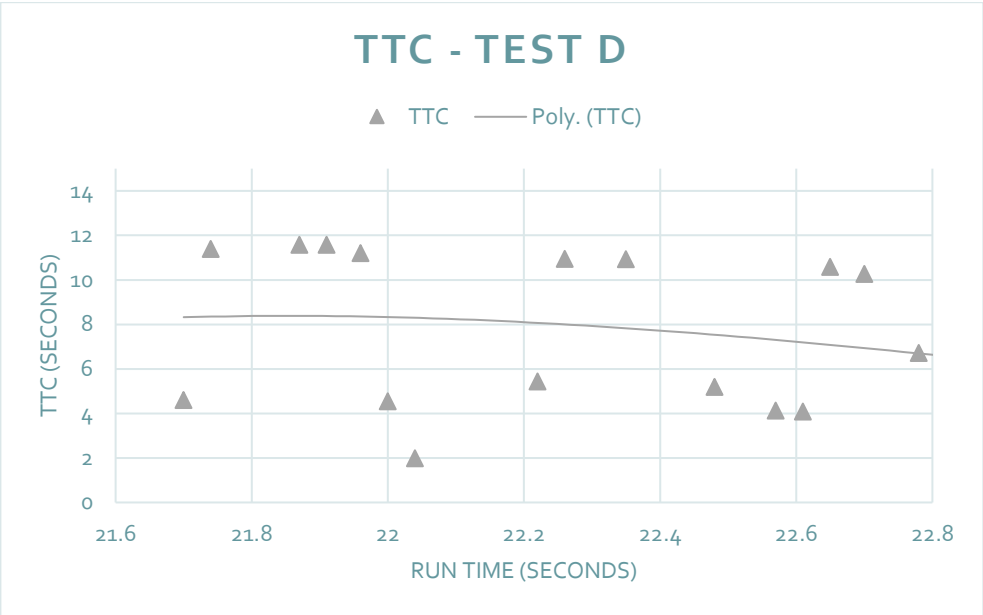


Figure 9: Plot of Time To Collision (TTC) during execution of test D

After the Lane Merge, while following the connected vehicle ahead, the AV gained velocity, while the leading car slowed down after passing the area of the lane merge. These coincidental occurrences caused a

decrease in the distance between the two vehicles, causing the TTC to drop below the threshold. That resulted in a visible response from the AV which, as seen in Figure 11 between 26.5 seconds until 27.5 seconds, reduced its velocity considerably and recovered its safety condition, measured by TTC, back into acceptable levels above the threshold.

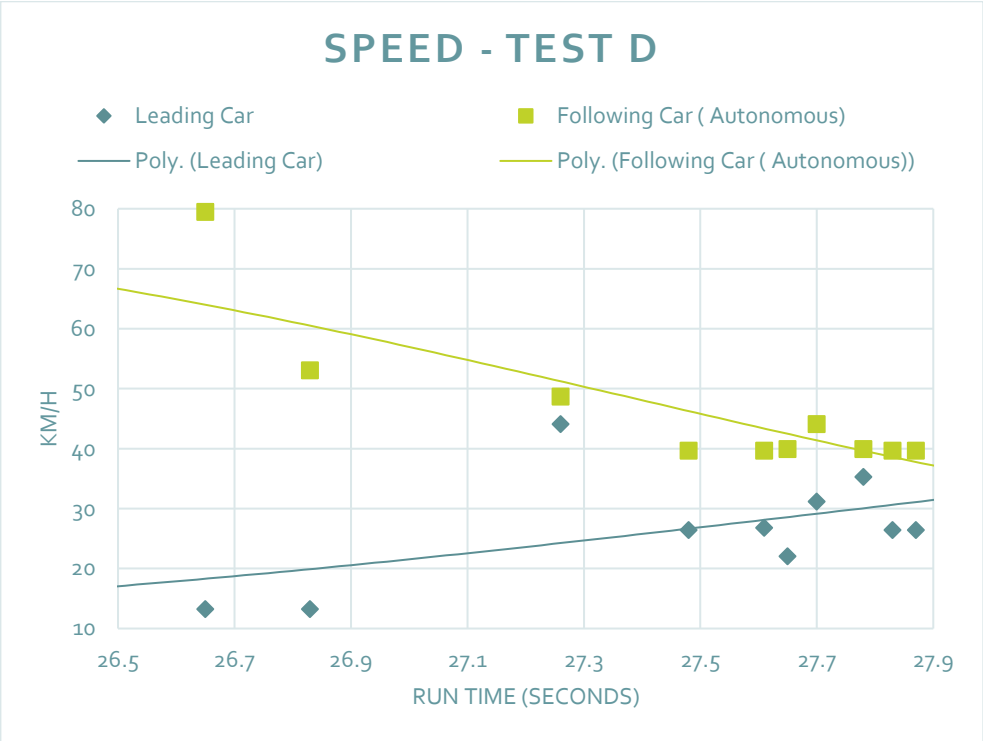


Figure 10: Plot of vehicles' speed after execution of test D

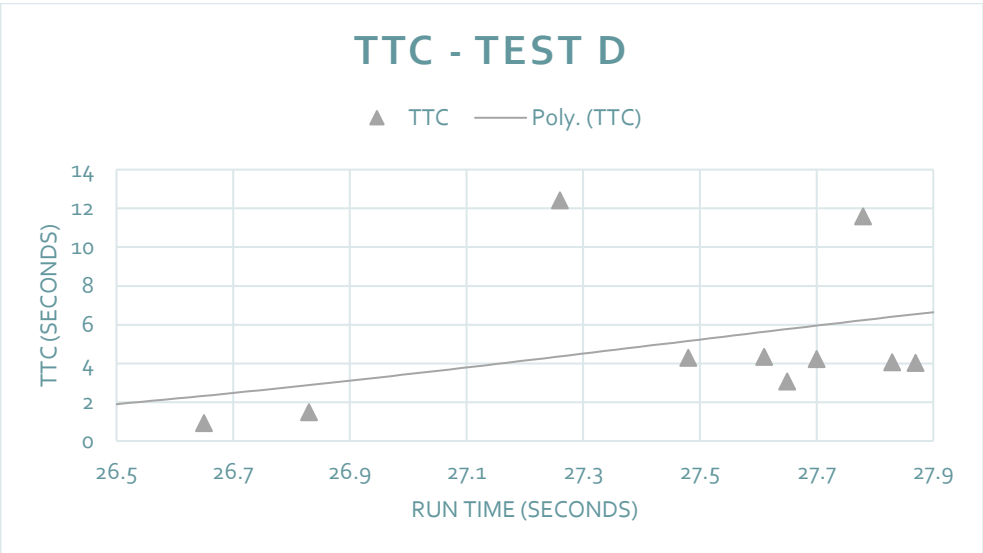


Figure 11: Plot of Time To Collision (TTC) after execution of test D

Similar to test D, in test E, both vehicles decreased their speed during the execution of the manoeuvre, as seen in Figure 12, improving the safety condition over time, as indicated by the TTC values in the graph below in Figure 13.
Test E video is available via the following link: https://youtu.be/mQY3hn_mtiM.

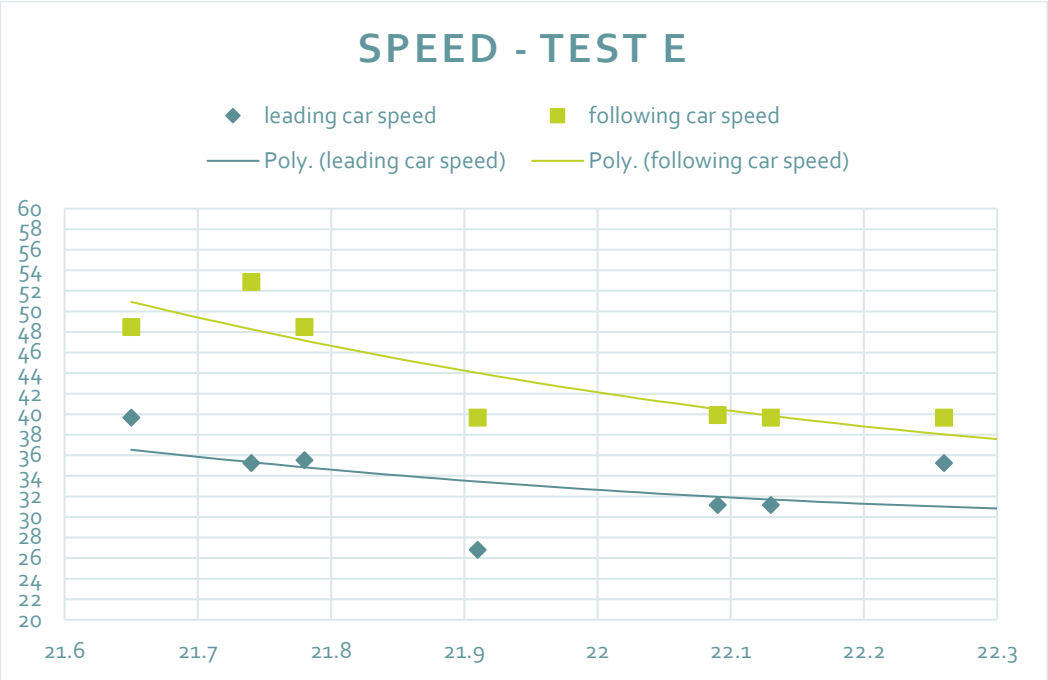


Figure 12: Plot of vehicles' speed during execution of test E

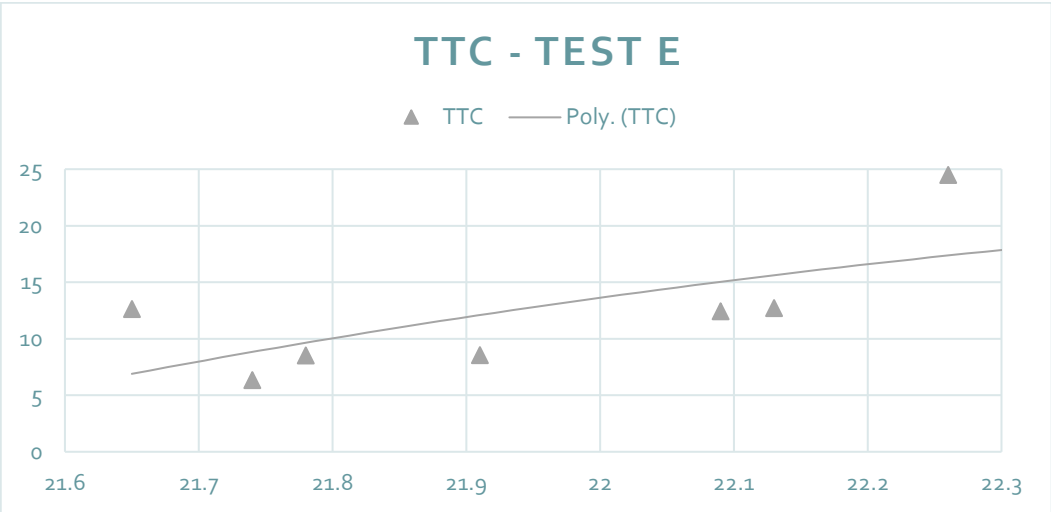


Figure 13: Plot of Time To Collision (TTC) during execution of test E

After the lane merge area, observed in test E, the speed difference between vehicles was not as large as in test D, resulting in a much safer condition as presented in test E TTC graph in Figure 15.

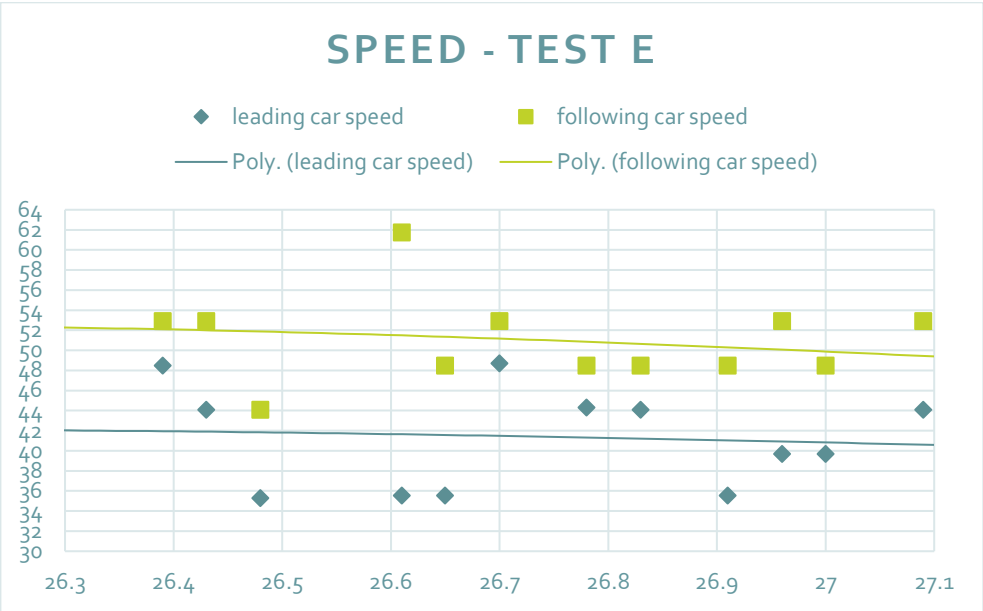


Figure 14: Plot of vehicles' speed after execution of test E

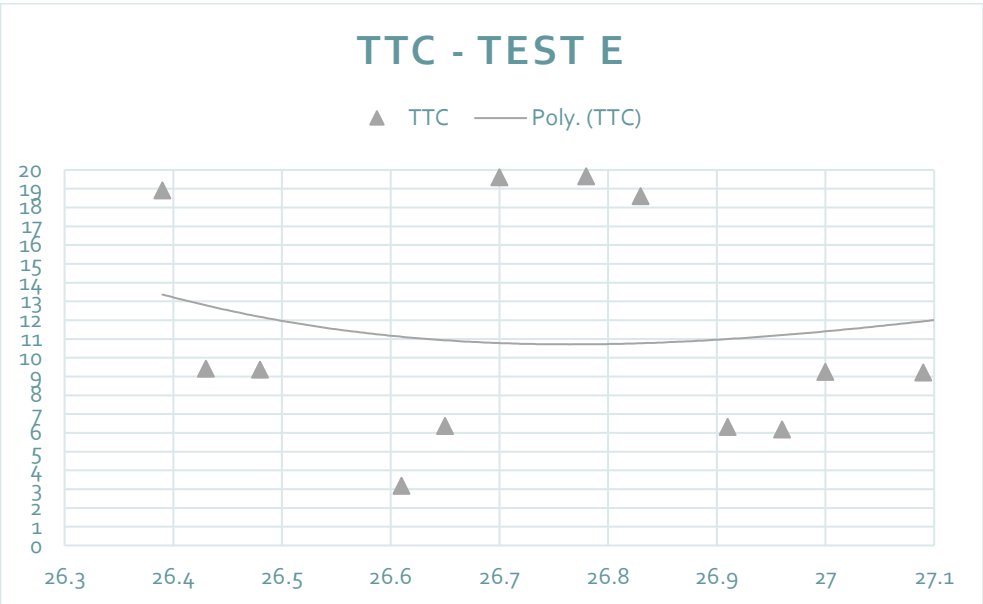


Figure 15: Plot of Time To Collision (TTC) after execution of test E

Other video analytics performed, for the lane merge use case, revealed safety conditions, where prerequisites for TTC were not met: The following car was not faster than the leading car or the trajectories were not conflicting. In these cases, the analysis did not produce any results, which is an indication that an

unsafe condition during the execution of the manoeuvre was not found. Such occurrence can be seen in test F video available via the following link: https://youtu.be/OZ7VDiNREIM.

3.7. Key findings and conclusions on the method development

Evaluation of the results obtained by video analytics of traffic safety conditions had a small amount of handover and quality video data available to correlate handover events with any incident in terms of traffic safety. Only one instance of a successful handover (Test A) was encountered to be performed prior to the manoeuvre captured in the videos that qualified for video analytics, while the rest of the videos that qualified had captured manoeuvres that we were unable to correlate with handover attempts data, due to unmatched timestamps between the video and the network events, or missing handover data of the network for the successfully captured manoeuvre. We have instances of similar test cases, Test A and Test B for example, where traffic safety conditions were met and vehicles' behaviour was very similar in both scenarios, when they were supported by a handover (Test A) and when they didn't receive that support (Test B). Even if this occurrence can provide some insight into the effects of 5G-supported CAM services during cross border events on traffic safety, it's not enough data to state any conclusion on impacts of 5G connectivity on the TTC. This outcome leads us to assume that the evaluation of the results of video analytics performed on these tests failed to determine the impacts of 5G connectivity on traffic safety during a handover.

Even though instances of unsafe conditions were detected in some videos, by occurrences of values exceeding defined parameters thresholds, they were quickly and efficiently resolved by the AV. No evidence was found to conclude that these instances were caused by 5G network issues. Challenging conditions at the trial site resulted in a limited number of recordings that had suitable image quality for this video analytics algorithm. The fact that these trials were conducted during the night, with limited illumination and uncertain handover location, caused many recording attempts to produce footage which did not meet prerequisites for video analytics to be performed.

The results obtained showcase the potential value that a method of overhead interpretation and analysis of traffic scenarios can provide. Combining with the systematic approach that video analytics offers, this method can deliver insights into incident prone occurrences or areas in traffic and allow for new technologies' impact on safety to be evaluated. Due to current legislative restrictions on fully automated vehicles on open public roads, some evidence of roadworthiness must be available to present the case for its acceptance. With that purpose, safety evaluations must provide evidence of this technology's compliance with safety standards and that safety conditions are met. Subsequent development of this methodology, by improving results at low illumination conditions, enhancing adaptability of the method to be applicable to a larger number of use cases, and possibly leveraging 5G networks to perform detection and generate alerts in real-time, can provide such evidence.

The trials executed during the night proved to be a challenge for video capturing even using the latest drone camera technology. The use of artificial lighting to improve visibility was attempted but it turned out that

this practice also creates glare and reflections that interferes with the quality of the footage. The trial site was located on a very prominent crossing of the border and it was necessary to close the roads during the trials. Thus, the trials had to be performed during the night period. This issue could have been avoided if access to permits for trials was easier and more sites were available. Additionally, if a more precise location for network handover had been achieved, it would have allowed for more video footage with higher quality data to be collected. These difficulties highlight the importance of carefully selecting trial sites, planning and testing in advance in various conditions and considering the logistical challenges involved in conducting experiments with emerging technologies. In the case of this experiment, the challenges faced during the trials resulted in insufficient quality in most of the video footage for the object detection algorithm to calculate distances, speeds, and subsequently safety parameters accurately. Therefore, future experiments should focus on selecting sites with optimal conditions for capturing high-quality footage and should take into account the impact of important factors such as instability of network and other concerns like road closures impacts on the success of the trials.

4. ASSESSMENT OF IMPACTS ON QUALITY OF LIFE

4.1. Quality of Life (QoL) assessment methodology

The Quality of Life assessment focused on assessing potential impacts of 5G-MOBIX enabled solutions in cross-border contexts on mode choice, travel time and throughput, traffic safety and emissions. The quality of life is studied from a societal rather than an individual perspective focussing on **impacts due to changes on the transport system level,** enabled or augmented with 5G enhanced automated driving. This approach thus considers benefits to society as a whole, as opposed to certain user groups. To cover also potential effects on user groups expected to benefit locally the most from the 5G connectivity enhancements, an example of estimating potential benefits in a specific context at the GR-TR border is given in Section 5. The goal in this type of estimation is not to systematically analyse all kinds of impacts in relation to a large traffic network as in QoL assessment, supporting for example traffic system development goals of a region or a country, but to focus on benefits that are relevant for the travellers or organisations regularly crossing the border.

The cross-border services of 5G-MOBIX enable seamless mobility across borders in automated vehicles. The QoL-evaluation focused on identifying impacts of 5G connected automated driving (CAD) compared to the baseline: connected automated driving with connectivity issues (in terms of session or service continuity). It needs to be noted that the deteriorated vehicle behaviour in the chosen baseline, CAD without 5G and corresponding service continuity solutions, such as those considered in the project, is theoretical, as it is not feasible that such a system would be deployed by manufacturers nor approved by authorities. AVs would need to be able to drive safely even in the absence of connectivity. Further, if faced with unstable or jerky driving of an AV, users might prefer to take over the driving task themselves. Nevertheless, the chosen baseline provides a helpful way to identify the unique effect of 5G on connected automated driving, instead of assessing potential impacts of (connected) automated driving compared to manual driving, or connected automated driving compared to automation without connectivity.

The unique impact of 5G compared to other forms of V2X communication lies in the low latencies, which enable its use for safety critical applications that are not possible with slower networks. Further, it is important to note that assessing the potential impacts of 5G-enhanced automated driving is challenging due to the novelty of both automated driving itself and 5G applied in automated driving. No empirical information yet exists on the behaviour of AVs (beyond SAE level 2), nor on AVs enhanced with connectivity realised by any means. Impacts of automated driving have mainly been studied with traffic simulations, which rely on various assumptions, as well as driver models inadequate for distinguishing manual and automated vehicle behaviour.

The QoL impact assessment is based on the method applied in the AUTOPILOT project [6] which piloted and evaluated automated driving enabled by Internet of Things (IoT). The methodology builds on the impact assessment framework for Automated Driving (AD) developed by the Trilateral ART WG (the Trilateral

Working Group on Automation in Road Transportation). The framework (Figure 16) is elaborated from Innamaa 2018 [10] and covers different impact areas (e.g. traffic safety, efficiency, personal mobility and equity) and includes both direct and indirect impacts of AD. It entails three blocks:

1. Use of AD (Acceptance and Transport system): relating to the acceptance and availability of AD. This block is not included in the assessment since these are preconditions for the 5G-Mobix services to exist

2. Mileage per mode (Vehicle operations, AD user, Quality of travel, Transport offering, Driving quality, and Behaviour and skills): determines the scope and size of impacts mechanism for the considered impact areas. This block is the focus of the assessment.

3. Impacts of transport system (Safety, Efficiency, Infrastructure, Environment, Travel behaviour, Land use Public health, (Individual) quality of life, and Equity): expected impacts on transport system level due to the changes in relating impact mechanisms of block 2.

The framework provides a comprehensive picture of both potential impact mechanisms and their pathways and ensures a systematic assessment. The approach is important for developing improved understanding on how new technologies and future services enabled by them may affect the traffic system and society at large. It may help in identifying the solutions with most impact on society, but also reveal risks for rebound effects of new technologies originally aimed at contributing to sustainability. A detailed description of the mechanisms of the framework can be found in APPENDIX B.

The method for assessing QoL-impacts in 5G-MOBIX included five steps (Figure 17):

- Step 1: Identifying relevant impact mechanisms for each considered impact area (mobility, safety, efficiency and environment) in the impact pathways figure (Figure 16). The impact pathways for the impact areas are based on previous research. The TeleFOT mobility model [11] was applied for personal mobility. For traffic safety, the nine impact mechanisms ([12], [13]) were applied. The pathways for efficiency and environment are based on literature and expert workshop carried out by Aittoniemi et al. [6]
- Step 2: Identifying relevant impact mechanisms, per use case where 5G is expected to have an effect when compared to the baseline (connected automated driving with connectivity issues). The mapping was done in expert workshops with T5.3 partners and use case leaders of the cross-border sites.
- Step 3: Combination of the outcomes of Step 1 and Step 2 to identify the relevant impact mechanisms of 5G for each use case and impact area.
- Step 4: Compiling available evidence (per use case) to describe potential impacts of 5G for each relevant impact mechanism and their potential directions (improve/decline, increase/decrease). Available literature[2] and other evidence from previous and ongoing projects (5GCroCo [14], 5G-CARMEN [15] , 5G-DRIVE [16], 5G-Safe Plus [17], L3Pilot [18], AUTOPILOT [6], CARTRE [19]) was used where applicable.

[2] In the end, little evidence was found from literature, due to the novelty of the 5G applications and driving automation itself. Literature on 5G in CAD is scarce and mostly limited to technical specifications and theoretical expectations of benefits.

- Step 5: Defining overall QoL implications of 5G assisted connected automated driving based on the results per use case.

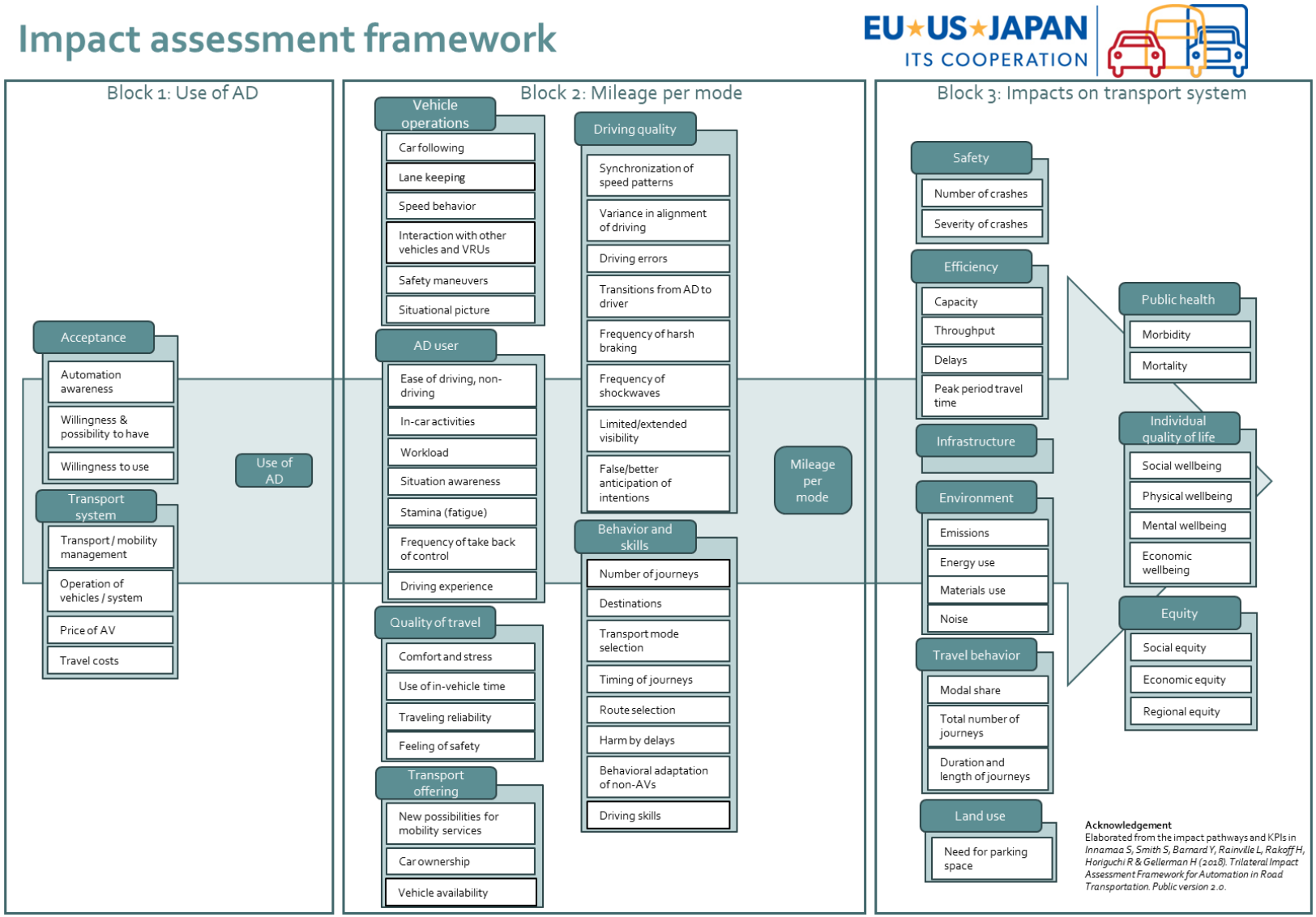


Figure 16: Basis of QoL-assessment: impact assessment framework of the Trilateral ART WG

Thus, the approach for the QoL impact assessment was from a high level and based on expert assessment supported by the available evidence. This was largely due to the nature of the trials and assessed use cases enabling seamless mobility in cross-border contexts and the focus in the project on technical evaluation. Therefore, several assumptions had to be done for the assessment. Firstly, the 5G-technology was assumed to be deployed and fully functioning. Secondly, the use cases were assumed to be widely available and in use. Lastly, each impact mechanism was considered one at a time, although there are overlaps and interactions between the different mechanisms of the framework. During the course of the project, the assessment scope was adjusted to focus more on the impact mechanism framework and the most important mechanisms where 5G is expected to have an effect.

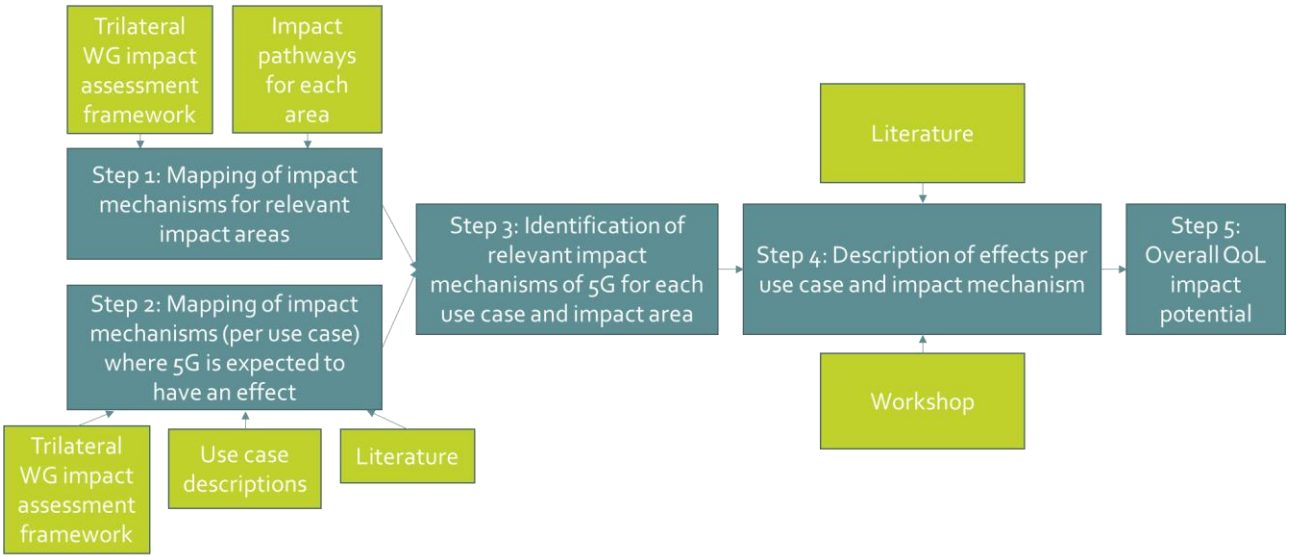


Figure 17: Overview of final QoL assessment methodology

4.2. Description of impact areas

4.2.1. Personal mobility

The term personal mobility describes the travel behaviour (and the reasons behind it) of individuals, including choice of destination and travel mode, to analyse the travel demand in a population on an aggregated level. Innamaa et al. 2013 [20] developed, as part of the TeleFOT project, a mobility model that is a theoretical tool built to identify and account for the relevant factors related to mobility. The model has been used in several projects such as DriveC2X [13], TEAM [21], AUTOPILOT [6] and L3Pilot [18]. The model includes three dimensions, which are in turn built upon different variables:

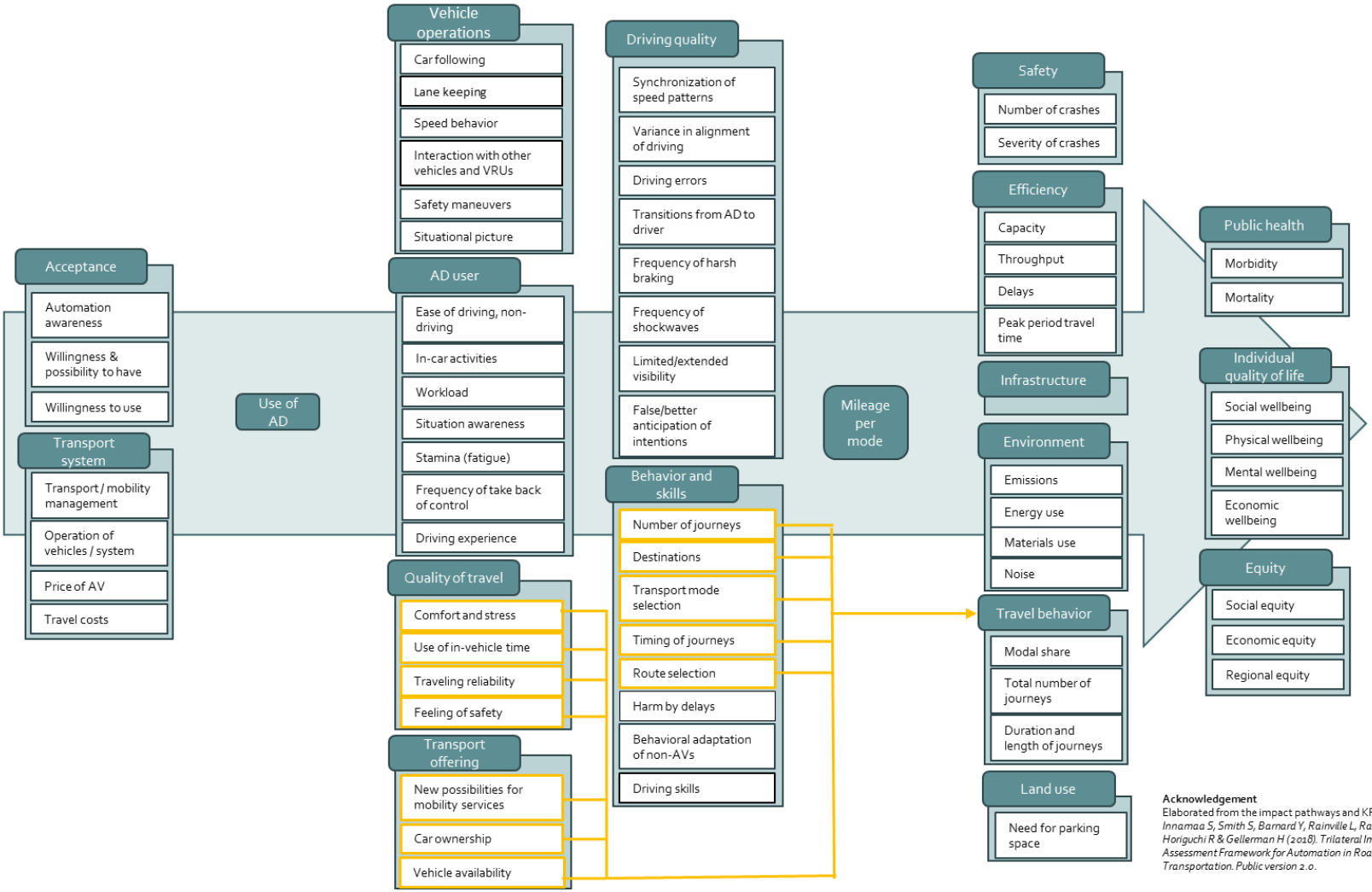
- Amount of travel (number of journeys, length of journeys, duration of journeys).
- Travel patterns (timing of trips, mode, route, adverse conditions).

- Journey quality (user stress, user uncertainty, feeling of safety, feeling of comfort).

The impact pathways of the mobility model [20] were mapped to the framework (Step 1) and are marked with yellow in Figure 18. In the interpretation of impacts from a personal mobility point of view, the basic principles from Innamaa et al. (2013) [20] were applied:

- Mobility improves as the number of journeys increases.
- Mobility improves as the length of journeys measured in distance or as duration decreases.
- Change in used modes either improves or reduces mobility based on user preference (whether they favour a car, public transport, etc.).
- Route choice either improves or deteriorates mobility based on user preferences (whether they favour a motorway, rural roads, etc.). It can be assumed that if the user is (voluntarily) willing to change route, he/she considers the new route better.
- Mobility improves as management of time budget for travelling improves, e.g. as departure time of commuting is shifted later.
- Mobility improves as travelling in adverse conditions such as darkness increases.
- Mobility improves as quality improves in terms of less stress and uncertainty or a better feeling of safety or comfort.

Impact pathways for personal mobility



Acknowledgement
Elaborated from the impact pathways and KPIs in *Innamaa S, Smith S, Barnard Y, Rainville L, Rakoff H, Horiguchi R & Gellerman H (2018). Trilateral Impact Assessment Framework for Automation in Road Transportation. Public version 2.0.*

Figure 18: Impact paths for personal mobility

4.2.2. Traffic safety

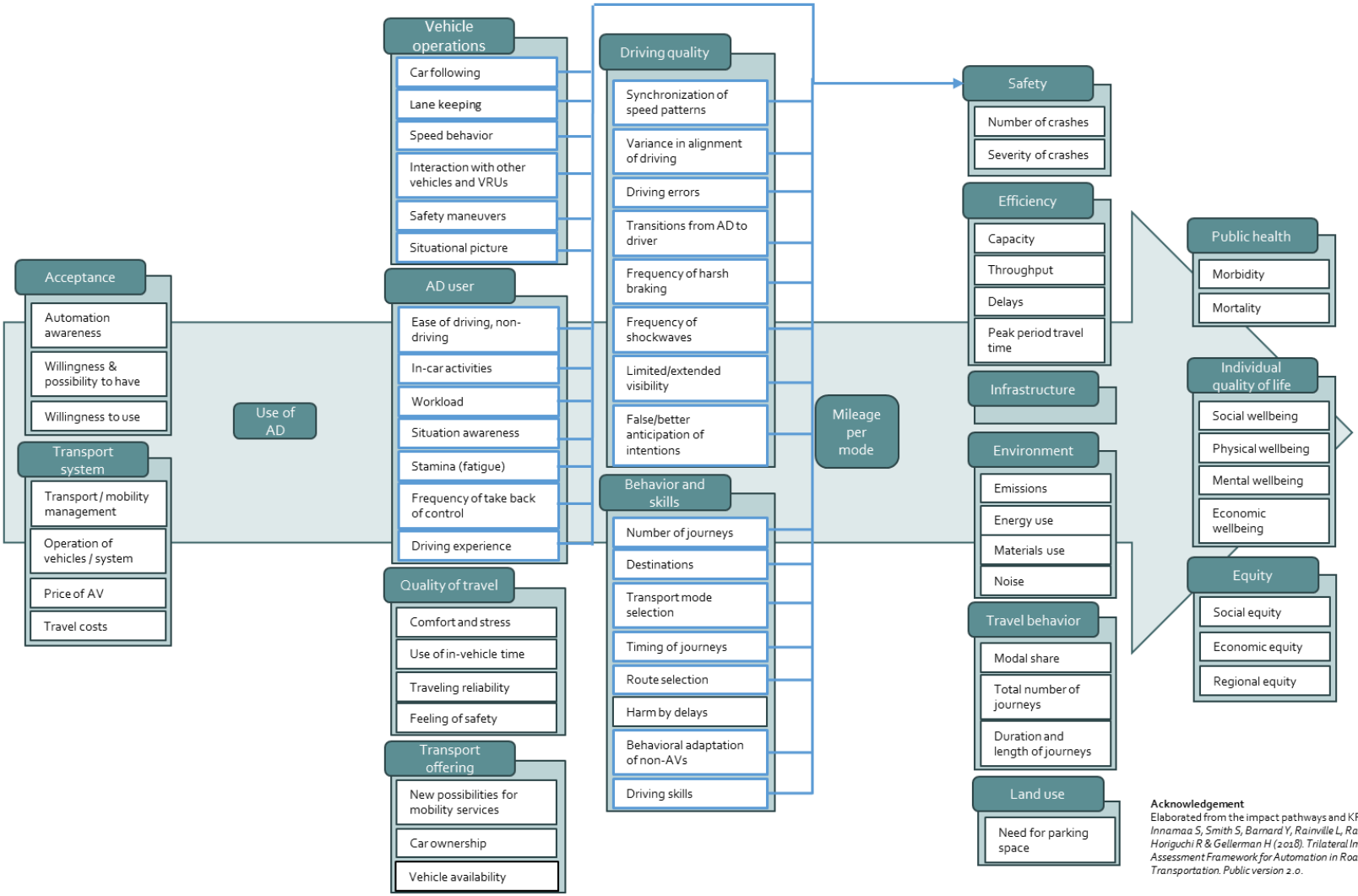
Traffic safety can be described in terms of the number of accidents, which is related to three main factors: exposure, risk and consequence [22]. Exposure represents the amount of activity where an accident can occur, risk is the expected number of accidents per unit of exposure and consequence is the severity of the accident. Traffic safety can, therefore, be influenced by a change in any of the three dimensions. Kulmala (2010) [12] proposed nine impact mechanisms for systematic ex-ante evaluation of the safety impacts of intelligent transport systems which Innamaa et al. 2018 [11] adapted for automated driving:

1. Direct modification of the driving task, drive behavior or travel experience.
2. Direct influence by physical and/or digital infrastructure.
3. Indirect modification of AV user behavior.
4. Indirect modification of non-user behavior.
5. Modification of interaction between AVs and other road-users.
6. Modification of exposure/amount of travel.
7. Modification of mode choice.
8. Modification of route choice.
9. Modification of consequences due to different vehicle design.

The mechanisms cover i) the three dimensions of traffic safety: risk (Mechanisms 1–5), exposure (Mechanisms 6–8) and consequence (Mechanism 9), ii) engineering and behavioral adaption and iii) indirect and direct impacts of both users and non-users. The traffic safety framework thus also includes changes in personal mobility of road users.

The impact pathways of the nine traffic safety mechanisms [11] [12] were mapped to the framework (Step 1) and are marked with blue in Figure 19.

Impact pathways for traffic safety



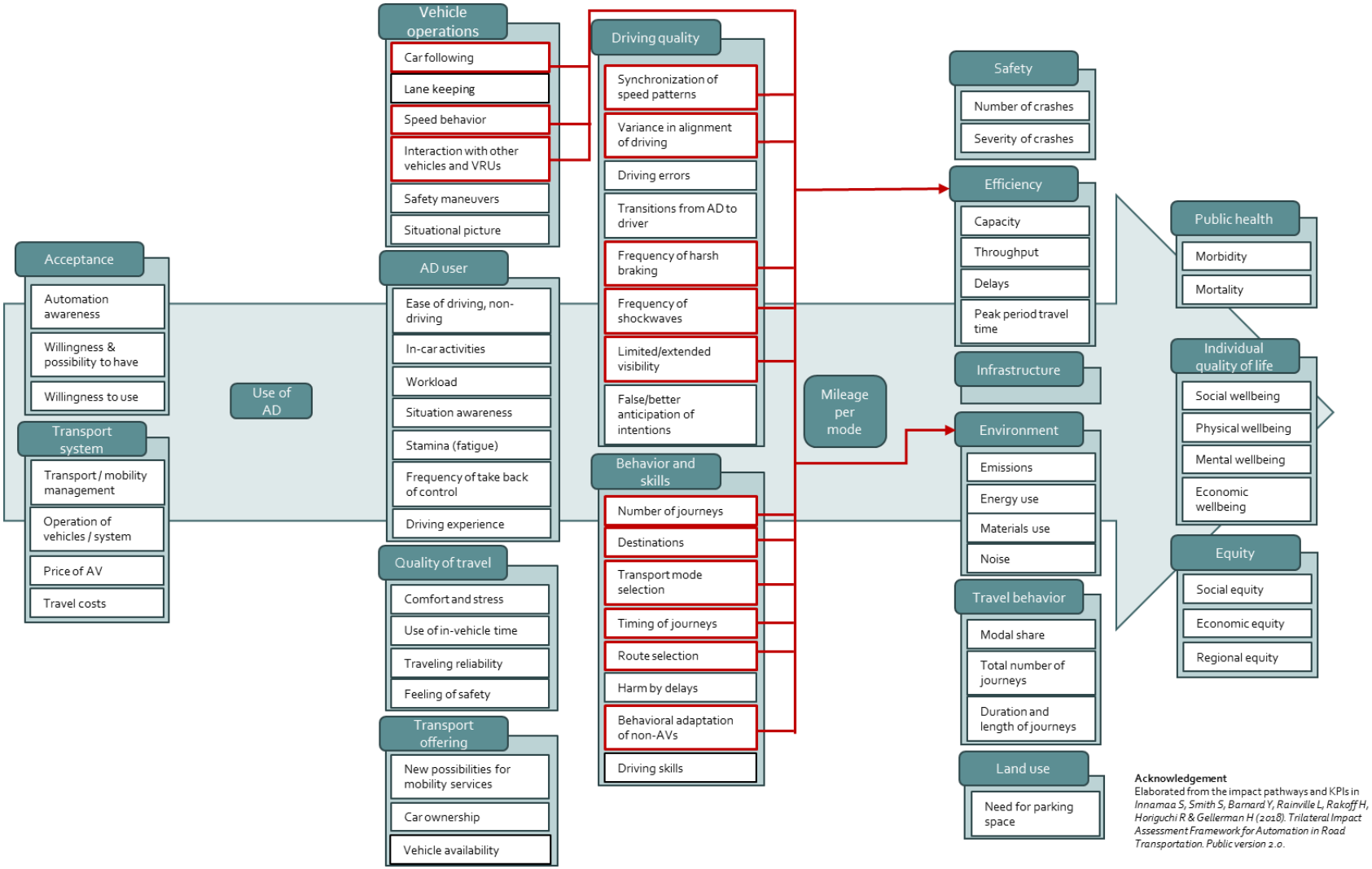
Acknowledgement
Elaborated from the impact pathways and KPIs in *Innamaa S, Smith S, Barnard Y, Rainville L, Rakoff H, Horiguchi R & Gellerman H (2018). Trilateral Impact Assessment Framework for Automation in Road Transportation. Public version 2.0.*

Figure 19: Impact paths for traffic safety

4.2.3. Efficiency and environment

Traffic efficiency describes how efficiently people and goods can move through the transport network. Efficiency can be measured by different indicators, such as capacity of a lane, link or intersection, throughput or traffic volume, travel time, delay time and travel time reliability [11]. Traffic efficiency is directly affected by the driving style, e.g. headways kept between vehicles, but also indirectly through mobility behaviour (e.g. amount of travel, mode choice, routes and destination choices) and traffic safety (potential reduction of delays caused by incidents). The environmental impacts of traffic include e.g. greenhouse gas emissions, particle emissions and noise. The CO_2 emissions of vehicles relate to the energy consumption which in turn depends on travel, driving conditions, and driver and vehicle behaviour. Specifically, emissions can be reduced by minimizing accelerations. Only tailpipe emissions are considered in the assessment.

The impact pathways for efficiency and environment, based on literature and expert workshop carried out by Aittoniemi et al. 2019, were mapped to the framework (Step 1) and are marked with red in Figure 20.



Acknowledgement
Elaborated from the impact pathways and KPIs in *Innamaa S, Smith S, Barnard Y, Rainville L, Rakoff H, Horiguchi R & Gellerman H (2018). Trilateral Impact Assessment Framework for Automation in Road Transportation. Public version 2.0.*

Figure 20: Impact paths for efficiency and environment

4.2.4. Findings from literature

As both driving automation and vehicle connectivity are emerging concepts and not yet widely deployed on the roads, the potential impacts of connected and automated driving have been studied mainly with traffic microsimulation using different models, assumptions and traffic compositions [23]. Studies typically use idealised conditions, often including only passenger cars, while heavy duty vehicles have a large impact on the traffic flow characteristics due to their larger size and mass. Studies differ in terms of the extent to which impacts are considered: only direct impacts from changes in the vehicle operations (driving behaviour) or including wider implications related to the amount of travel, shift in travel modes, type of deployment (car- and ridesharing) or changes in vehicle size and propulsion [24], [25].

Generally, literature on CAM suggests that benefits can be achieved, with benefits on traffic flow level requiring a high penetration rate of connected and automated vehicles. Improvements in driving efficiency can be outweighed by increase in the amount of travel by cars. Literature suggests that depending on the type of deployment and take up, CAM can improve capacity of motorways [26], reduce conflicts and critical events [27], [28] and reduce emissions and fuel consumption [25]. On the other hand, CAM services can also influence personal mobility behaviour and lead to increased car usage, so this must be considered when looking at the benefits of these services [24]. Benefits are dependent on the characteristics of vehicles, market penetration rate and traffic and road network characteristics [29]. There is general consensus in literature that a high share of connected and automated vehicles is needed for any benefits to realise [30], [31]. Shladover (2021) [31] suggests that 70% market penetration is needed for achieving half the benefits of full penetration.

The focus in the literature studies is mostly on impacts of CAM compared to all vehicles being manually driven, or in some cases comparing impacts rising from connected automated vehicles to those from non-connected automated vehicles. Further, the use cases generally do not correspond to the user stories of 5G-MOBIX as presented in Section 0. For these reasons, existing literature is of limited relevance to the QoL assessment in 5G-MOBIX.

While 5G has received attention in recent research, the 5G use cases considered have not focused specifically on societal impacts of 5G enabled CAM. CAM is usually included as one potential area of benefits. For example, short summaries of potential impacts of CAM in general from literature were given in 5GCroCo [14]. 5G Norma [32] made assumptions on safety and emissions benefits of CAM without elaboration of the underlying method. Therefore, results from these projects were not considered useful for the 5G-MOBIX QoL assessment.

4.3. Considered user stories/scenarios

The quality of life assessment of 5G-MOBIX use cases was based on the use case descriptions developed by T5.4 (User Acceptance), since these allowed to illustrate the services from an end user point of view. Furthermore, this harmonised the approach among the different evaluation tasks. The T5.4 use case descriptions were summarised to describe the main functionalities of the service. The baseline description describes what the use case is compared to (connected automated driving with connectivity issues). The baseline descriptions were based on the average and worst case scenarios developed as part of T5.4 (D5.4 Annex 1 [3]).

Identifying the consequences of the connectivity issues of connected and automated driving in the baseline enabled identifying the potential issues that connected automated driving with 5G can address. The assessed user scenarios, their baselines and expected consequences to both the connected and automated vehicle itself and to other road users are shown in Table 3.

Table 3: Description of evaluated use case and baseline per user scenario

User scenario (US)	Baseline	Consequences, own vehicle	Consequences, others	US description with 5G
Lane merge & overtaking	Vehicle receives **delayed information** on upcoming end of lane or approaching vehicle on the left lane. Vehicle **slows down or follows the car in front** until connectivity is regained, or there is a clear view for the sensors, and then performs the manoeuvre.	Vehicle slows down or follows the car in front, jerky driving	Small; Slower speed, Jerky driving, potential conflicts	Vehicle receives information on upcoming end of lane and slower car. Vehicle **can automatically adapt speed and perform lane change**.
HD maps	Due to connectivity issues, the vehicle does not receive updated information and will **request you to take control of the vehicle**.	Take over request (TOR)	Consequence of TOR, slowing down, disturbance, potential conflicts	Vehicle receives information on upcoming road works. Vehicle **can maintain automated driving** through road works.
Automated shuttle remote driving across borders	Remote driver receives **delayed information** from shuttle, and their commands reach the vehicle with a delay. This may cause the **vehicle movement to be jerky**, with some **hard braking and late acceleration**. Vehicle receives delayed information from the	Unstable movements, hard braking	Possible conflicts, disturbance, comfort and stress / feeling of safety	Vehicle receives information on upcoming obstacles and VRUs in vicinity and can **reroute**.

	pedestrian. This may cause the vehicle to **brake sharply**.			
Platooning with "SWIS"-functionality in cross-border settings	The image streaming from the platoon leader loses resolution, although you will still be able to see the road. Also, the following ability of your truck is impaired and the **trajectory becomes a bit jerky**. Eventually, you may **need to intervene**.	Jerky trajectory, takeover, longer gap to leader	Disturbance/ inconvenience, slowing down, consequences of TOR	Following a lead vehicle by **platooning and receiving view** of the leader's windshield.
Truck routing	Vehicle driving in automated mode through border control facility. Due to poor network connectivity, the dynamic map is unstable and the **speed might need to be reduced**.	Reduced speed or takeover	Reduced speed, inconvenience, queues at border	Vehicle **driving in automated mode** through border control facility **with routing ability**. The vehicle is controlled from the cloud until the X-ray building by using e.g. sensor information from RSU.
Extended sensors for assisted border-crossing	Automatic inspection is not possible. Vehicle **driving in manual mode** within border facility.	Driving in manual mode	none (from CAD)	Automatic information exchange for inspection rating, routing instructions to correct line and location information of border agents. Inspection procedure according to rating (low risk -> no contact with agents, suspicious -> automatic or manual inspection). Vehicle **driving in automated mode** within border facility.

The user scenario "Extended sensors for assisted border crossing" was left out of the QoL assessment as it was considered of little relevance from a traffic perspective. However, automatic inspection is certainly beneficial for the efficiency of border processes, and thus it can be significant for specific traveller groups, transport and logistics industry and border control authorities. Potential time saving benefits of this user scenario are discussed separately in Section 5.

4.4. QoL Results

4.4.1. Complex manoeuvres in cross-border settings (lane merge and automated overtaking)

Figure 21 summarises i) the impact mechanisms of the framework (Block 2) where 5G was expected to have an impact compared to a connected automated driving without 5G and ii) the implications on to the considered impact areas (personal mobility, traffic safety and efficiency and environment). The figure shows the potential impact mechanisms of 5G for "Complex manoeuvres in cross-border settings (lane merge and automated overtaking" and their relation with the impact areas. The fully coloured boxes indicate direct impacts, while striped boxes indicate more indirect or secondary impacts. The expected impacts of 5G and the related implications for each of the considered impact areas are elaborated below.

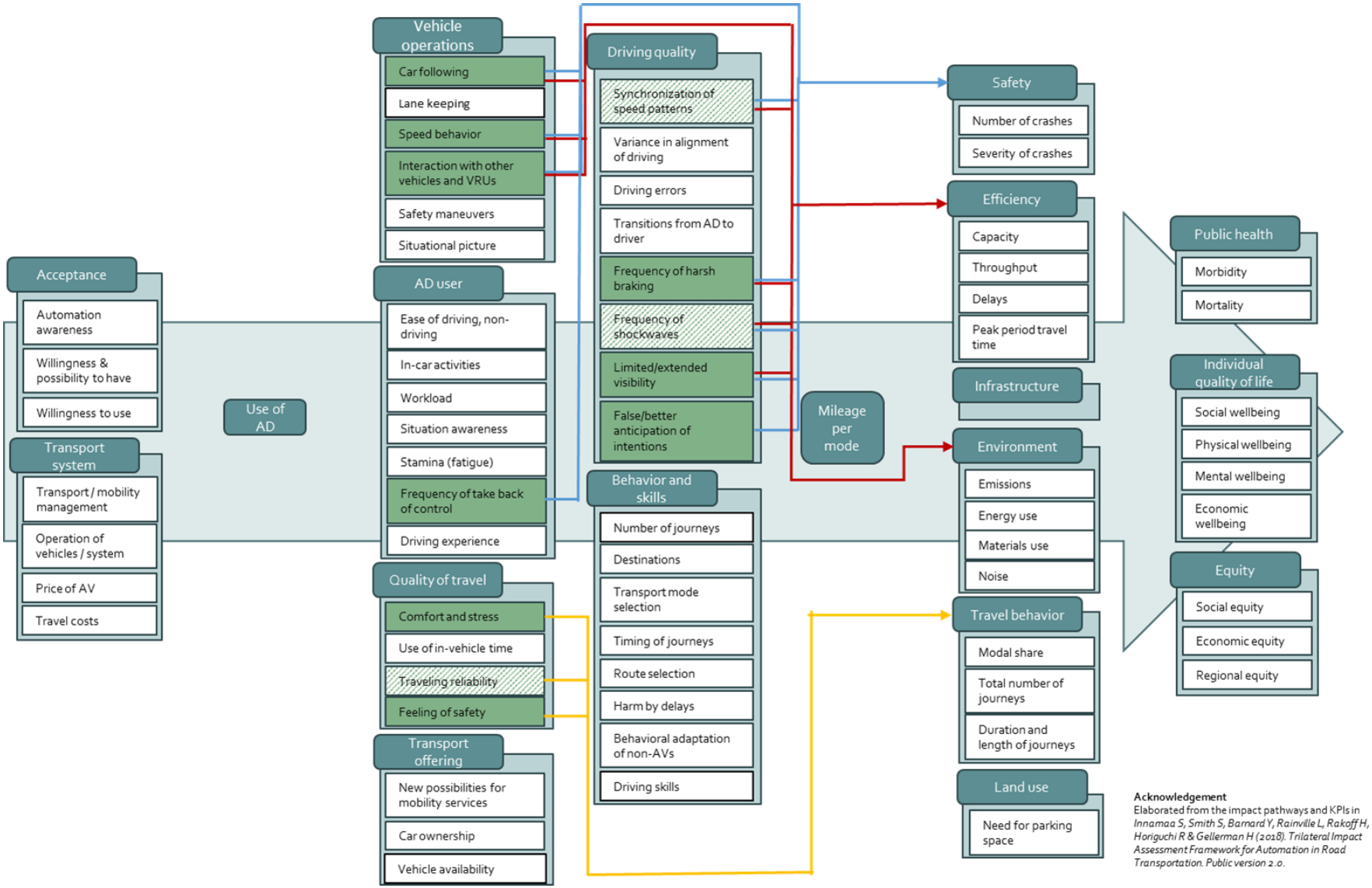


Figure 21: Results for "Lane merge and automated overtaking"

Expected impacts of 5G:

5G connectivity is expected to enable CAVs to automatically adapt speed to that of a slower car ahead and perform merging operations or change lanes. This is expected to affect the mechanisms of speed behaviour and interaction with other vehicles and VRUs (Vehicle operations). The smoother speed profile may change frequency of harsh brakings, extend visibility and enhance anticipation of intentions (Driving quality). In some conditions, synchronisation of speed patterns and frequency of shockwaves may be affected. The need for takeover requests to the driver becomes less likely (AD user). Comfort and stress as well as feeling of safety are likely to change, in some conditions also traveling reliability (Quality of travel). The mechanisms of Transport offering or Behaviour and skills are not expected to change with the use case Complex manoeuvres in cross-border settings.

Implications for quality of life:

Changes in the mechanisms of Vehicle operations and Driving quality are expected to affect the safety, efficiency and environment impact areas. Improved interaction with other vehicles and enhanced visibility and anticipation of intentions are likely to improve safety, while the lack of slowing down is beneficial for traffic efficiency. Smoother speeds and less brakings are likely to cause less emissions due to decrease in acceleration. Regarding mobility, changes are expected through improved comfort and feeling of safety.

4.4.2. Complex manoeuvres in cross-border settings: HD maps

Figure 22 summarises i) the impact mechanisms of the framework (Block 2) where 5G was expected to have an impact compared to a connected automated driving and ii) the implications on to the considered impact areas (personal mobility, traffic safety and efficiency and environment). The figure shows the potential impact mechanisms of 5G for "Complex manoeuvres in cross-border settings: HD maps" and their relation with the impact areas. The fully coloured boxes indicate direct impacts, while striped boxes indicate more indirect or secondary impacts. The expected impacts of 5G and the related implications for each of the considered impact areas are elaborated below.

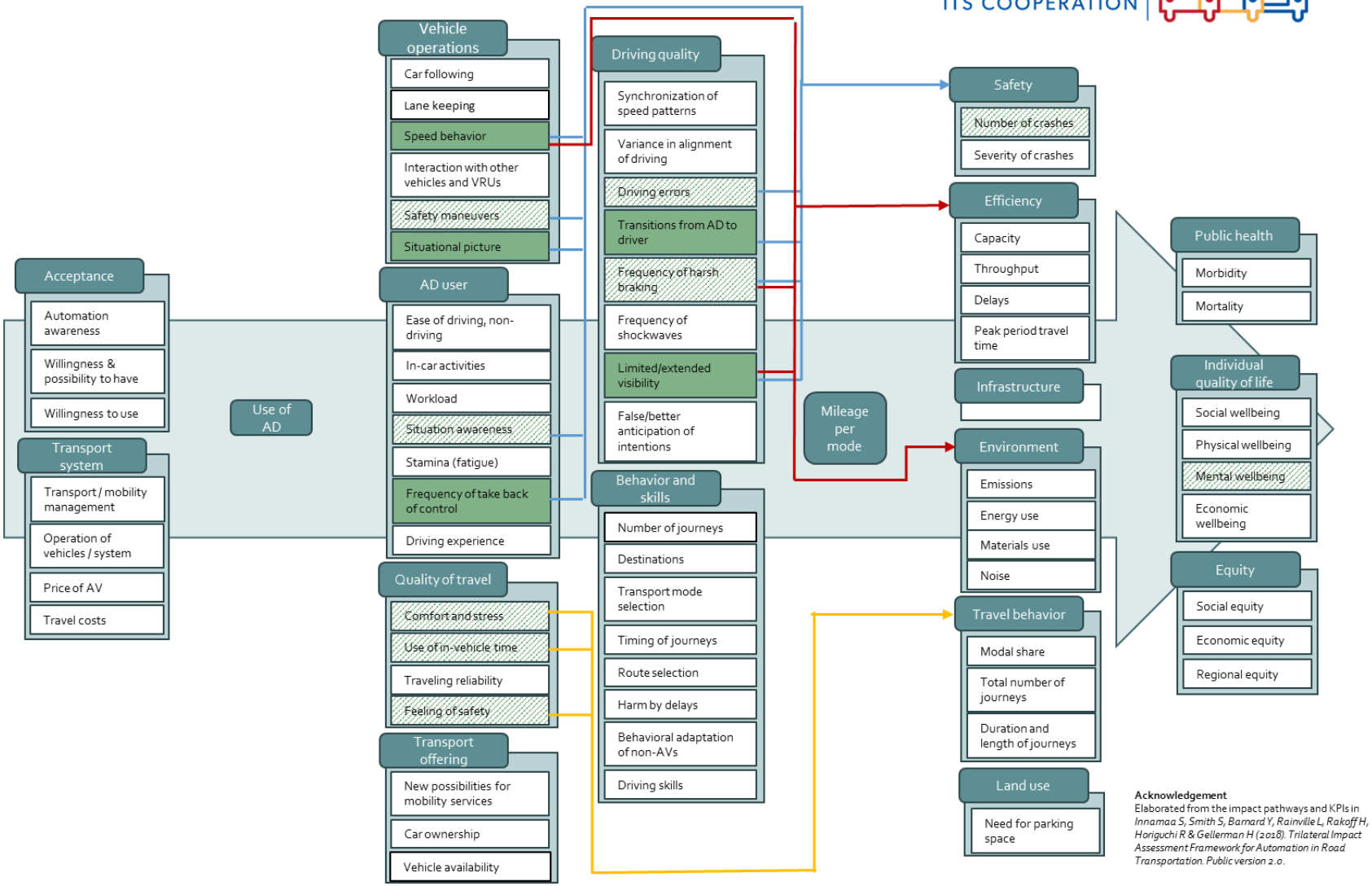


Figure 22: Results for "Complex manoeuvres in cross-border settings: HD maps"

Expected impacts of 5G:

Without 5G connectivity, the HD maps user scenario leads to a takeover request to the driver as the vehicle does not receive updated information on the situation on the road. The consequences of take-over requests are not yet well known, but they may lead to a vehicle slowing down while the driver prepares to resume driving. With 5G connectivity, the vehicle could remain in automated mode even through road works, leading to changes in mechanisms related to Vehicle operations (car following, speed behaviour, interaction with other vehicles), Driving quality, Frequency of take back control (AD user) and Quality of travel.

Implications for quality of life:

Smoother speed with less brakings is expected to improve traffic efficiency and environmental impacts. Less braking, less takeovers and better knowledge of the area improve traffic safety. The travel experience may be improved through increased feeling of safety and comfort and more reliable travel times.

4.4.3. Automated shuttle remote driving across borders

Figure 23 summarises i) the impact mechanisms of the framework (Block 2) where 5G was expected to have an impact compared to a connected automated driving and ii) the implications on to the considered impact areas (personal mobility, traffic safety and efficiency and environment). The figure shows the potential impact mechanisms of 5G for "Automated shuttle remote driving across borders" and their relation with the impact areas. The fully coloured boxes indicate direct impacts, while striped boxes indicate more indirect or secondary impacts. The expected impacts of 5G and the related implications for each of the considered impact areas are elaborated below.

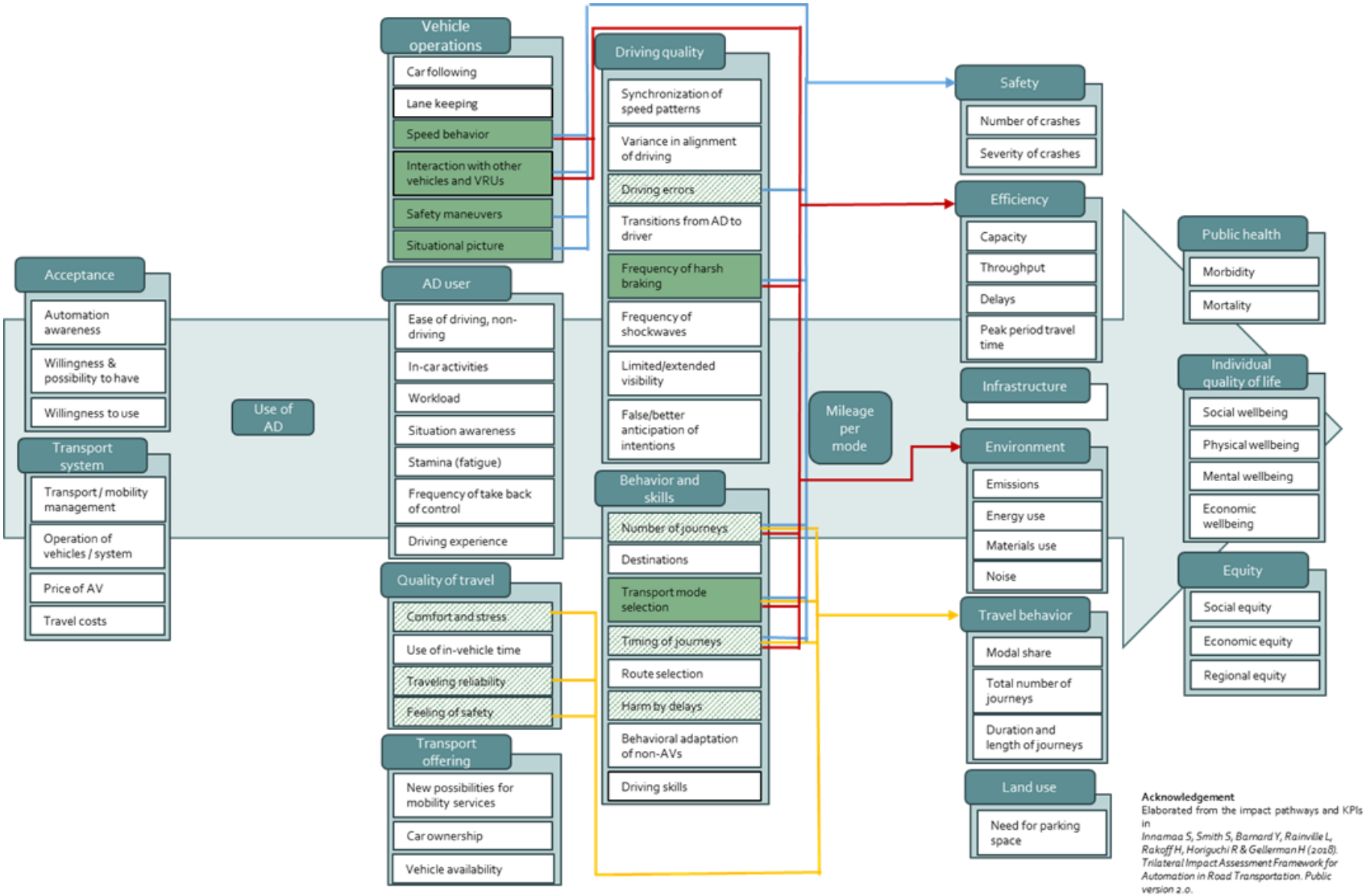


Figure 23: Results for "Automated shuttle remote driving across borders"

Expected impacts of 5G:

5G connectivity is expected to reduce delay in information received by the remote driver of the shuttle. This would likely affect speed behaviour, interactions with other vehicles and safety manoeuvres, and improve the situational picture of the remote driver (Vehicle operations). The frequency of harsh brakings might reduce (Driving behaviour). Due to the smoother travel, people might change their travel behaviour in terms of transport mode selection or number and timing of journeys (Behaviour and skills). Quality of travel might improve due to changes in comfort and stress and feeling of safety of passengers as well as improved traveling reliability.

Implications for quality of life:

Safety might be improved due to the better situational picture of the remote driver and less frequent harsh brakings. More constant and higher driving speeds and less frequent harsh brakings could also improve traffic efficiency. Less harsh braking might also reduce emissions. Personal mobility choices could be affected by the more comfortable and reliable travel experience.

4.4.4. Platooning with "see what I see" functionality in cross-border settings

Figure 24 summarises i) the impact mechanisms of the framework (Block 2) where 5G was expected to have an impact compared to a connected automated driving and ii) the implications on to the considered impact areas (personal mobility, traffic safety and efficiency and environment). The figure shows the potential impact mechanisms of 5G for "Platooning with "see what I see" functionality" and their relation with the impact areas. The fully coloured boxes indicate direct impacts, while striped boxes indicate more indirect or secondary impacts. The expected impacts of 5G and the related implications for each of the considered impact areas are elaborated below.

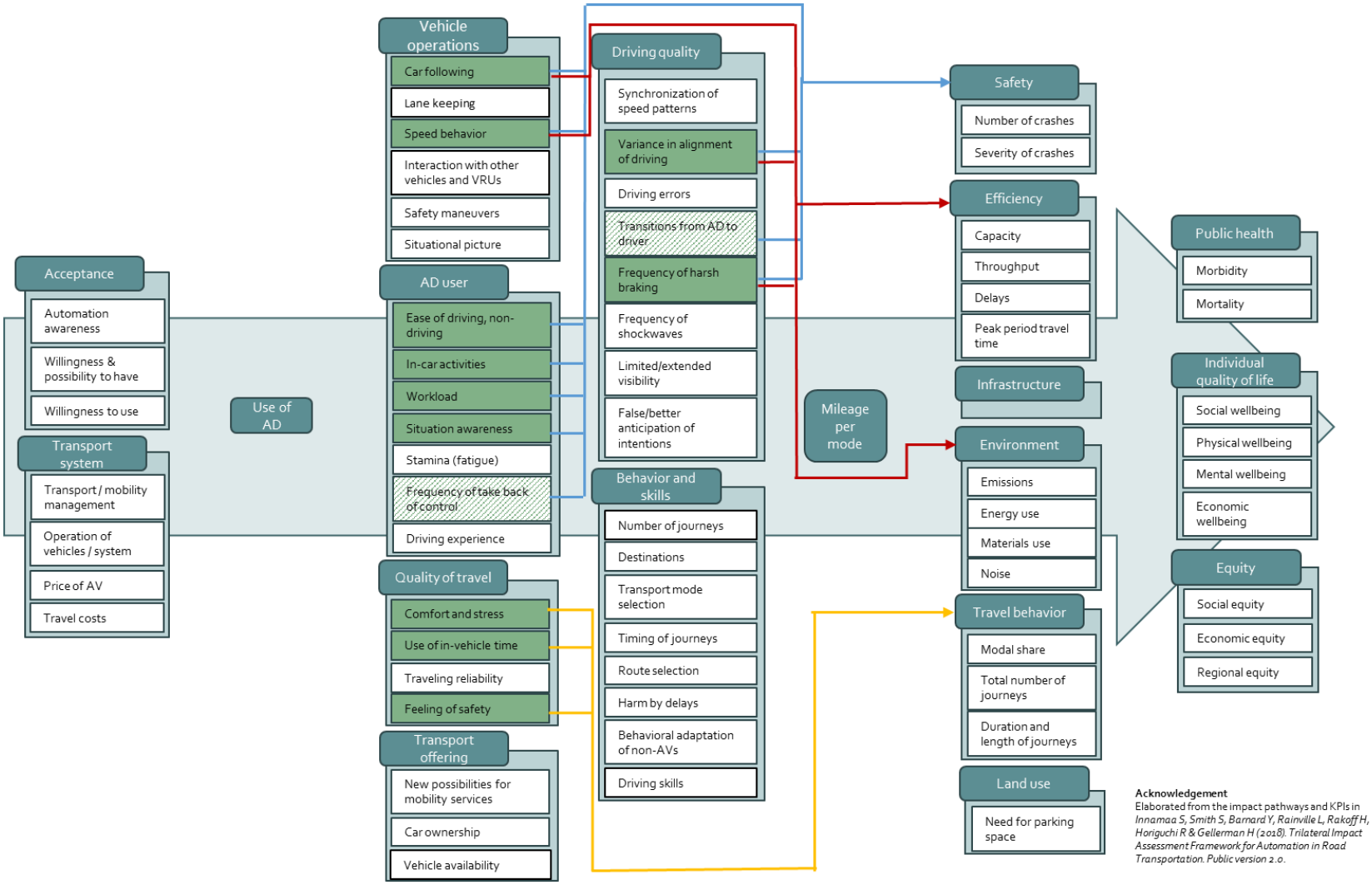


Figure 24: Results for "Platooning with "see what I see" functionality"

Expected impacts of 5G:

With 5G connectivity, the truck platooning can work as intended without jerky trajectories or the need for the driver to intervene. Vehicle operations in terms of car following and speed behaviour are improved. Driving quality is affected through better alignment of the vehicles in the platoon, potentially less harsh brakings and changes in transition of control. The driving in terms of ease of driving, in-car activities, workload and situation awareness of the driver as well as frequency of take back of control are likely improved (AD user). Quality of travel in terms of comfort and stress, use of in-vehicle time and feeling of safety also might improve.

Implications for quality of life:

Smoother driving in terms of car following and speed behaviour as well as less harsh braking is expected to improve both traffic safety and efficiency. Impacts on the environment depend on the extent and direction of the changes in speed and harsh brakings. As this use case considers only professional drivers, personal mobility impacts are not relevant. However, the driving experience of the professional drivers might improve.

4.4.5. Truck routing

Figure 25 summarises i) the impact mechanisms of the framework (Block 2) where 5G was expected to have an impact compared to a connected automated driving and ii) the implications on to the considered impact areas (personal mobility, traffic safety and efficiency and environment). The figure shows the potential impact mechanisms of 5G for "Truck routing" and their relation with the impact areas. The fully coloured boxes indicate direct impacts, while striped boxes indicate more indirect or secondary impacts. The expected impacts of 5G and the related implications for each of the considered impact areas are elaborated below.

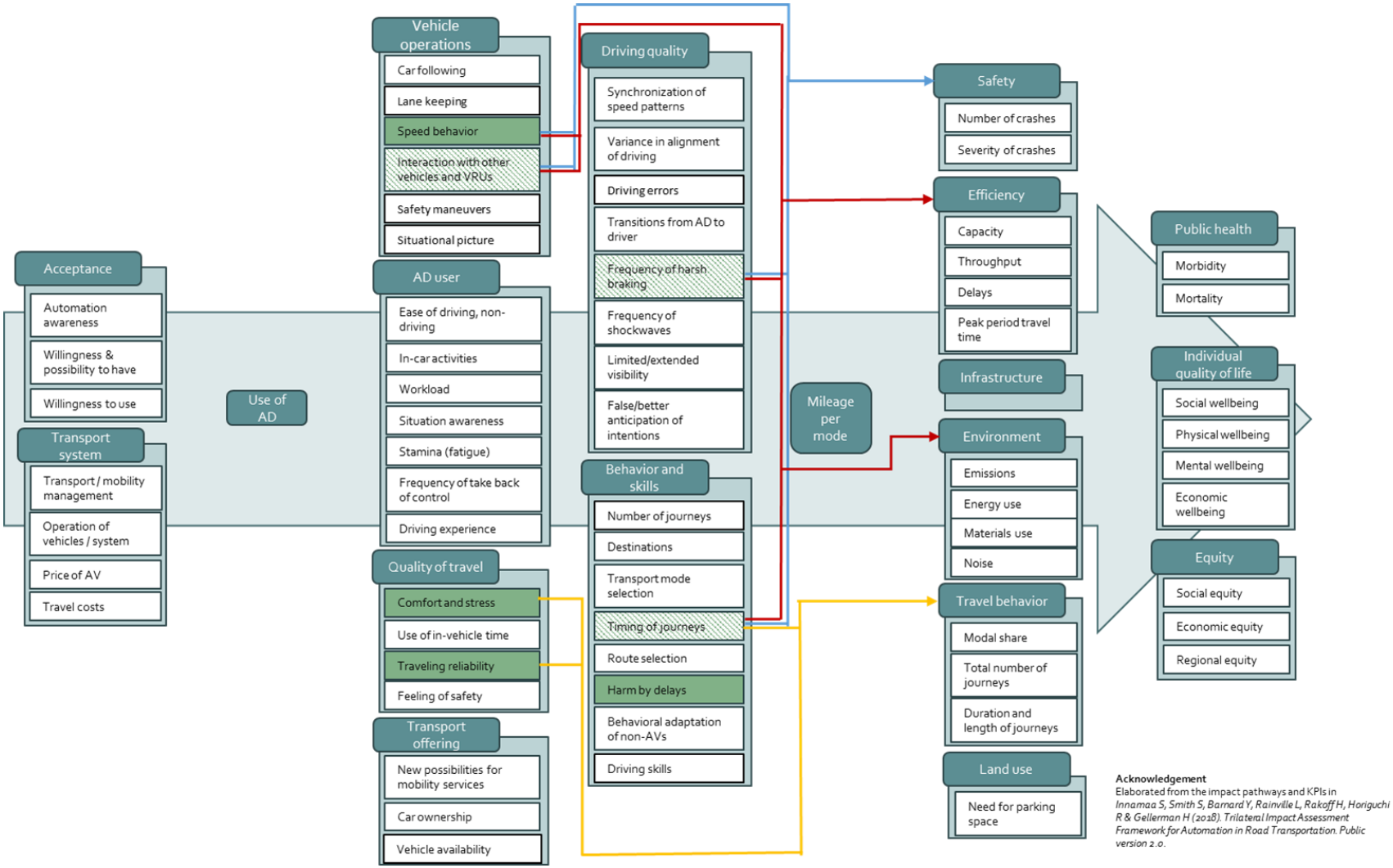


Figure 25: Results for "Truck routing"

Expected impacts of 5G:

5G connectivity is expected to enable higher speed within the border facilities, which may affect interaction with other vehicles and VRUs (Vehicle operations). The frequency of harsh brakings might be reduced (Driving quality). Removing the need for driving slowly, harm by delays would reduce (Behaviour and skills), and comfort and stress and traveling reliability improve (Quality of travel).

Implications for quality of life:

The scope of this use case is limited to trucks directly in the border control facilities, and therefore impacts on quality of life are limited. In heavily frequented border crossings, delays might be reduced, improving traffic efficiency and the personal mobility experience. Changes in speed and frequency of harsh braking would also affect safety.

4.6. Frequency and size of effects

The potential frequency of the 5G-MOBIX user scenarios in traffic in cross-border situations as well as an estimate of the effect size with 5G were elaborated in an expert workshop (Table 4). The table shows that the frequency for lane merge and overtaking scenarios is considered to be medium. The other scenarios have a low frequency. Frequencies might change if truck platooning was widely deployed in the heavy vehicle fleet or if automated shuttles were frequently in use across borders. Similarly, the size of the effect with 5G on quality of life (safety, efficiency, environment, mobility) is generally considered to be medium or small, in comparison to the baseline (connected automated driving with connectivity issues). **Note that the frequency of situation and size of effects might be large in a local context for specific users, but the assessment here is concerned with the overall effects on traffic system level**. Section 5 presents an example of estimating benefits of the user story *Extended sensors for assisted border crossing*, concerning only the Greece-Turkey border crossing situation and the perspective of travellers and personnel there.

Table 4: Assessment of frequency and size of effect of 5G-MOBIX solutions on Quality of Life

User scenario	Frequency in traffic in cross-border situations	Size of effect with 5G
Lane merge & overtaking	Medium	Small Locally medium
HD maps	Low	Medium Potentially positive for safety
Automated shuttle remote driving across borders	Low	Medium
Platooning with "SWIS"-functionality in cross-border settings	Low	Small Positive for environment
Truck routing	Low	Small Positive for comfort and travel time (efficiency of border processes)
Extended sensors for assisted border crossing	High (but not relevant for CAM)	Very small, Travel time+, efficiency of border processes

4.7. Concluding remarks

The Quality of Life assessment focused on identifying impact mechanisms, through which the 5G-MOBIX enabled solutions in cross-border contexts could affect mode choice, travel time and throughput, traffic safety and emissions. The assessment identified impacts of 5G connected automated driving in comparison with the baseline of connected automated driving with connectivity issues in terms of session or service continuity. Although theoretical, the approach enabled identifying the unique effects of 5G.

Literature on 5G for CAM is scarce and mostly limited to technical specifications and theoretical expectations of benefits. Tests with single or few equipped vehicles, as applied in pilot projects such as 5G-MOBIX, do not allow for making conclusions on traffic in general with a large percentage of equipped vehicles. Therefore, the QoL assessment focused on the potential impact mechanisms through which impacts are likely expected. Results of the QoL assessment should be seen as indicative only.

When assessing impacts of changes to the traffic system such as the addition of connected and automated vehicles to traffic, it is important to take into account both the potential effectiveness of the measure as well as the prevalence of the relevant situation in the transport system or network. The prevalence of cross-border situations in the broader context (i.e. a large traffic network) is small. However, from the subjective view of specific travellers, drivers or companies crossing borders regularly the perceived benefits may be highly relevant. These benefits are the bases e.g. in the value propositions of the service providers, often targeted to specific customer groups and contexts.

In a local context, the impacts depend on the traffic conditions. Effects of more constant speed are more relevant in heavy traffic conditions than on empty roads. Nevertheless, effects can be relevant in specific situations (such as road works) or for certain users, especially those traveling frequently across borders. Small improvements for traffic safety and efficiency are possible. The user scenario with most effects is *Lane merge and automated overtaking* because those situations were quite frequent also in cross-border context.

Based on the results of the assessment, the most important mechanisms of 5G in the 5G-MOBIX user scenarios are the following:

- Vehicle operations: Speed behaviour, interaction with other vehicles and VRUs
- Driving quality: Frequency of harsh braking
- Quality of travel: Traveling reliability (reliability of travel time)

The anticipation enhanced by 5G can lead to avoiding takeovers and jerky trajectories, keeping a more constant speed, avoid harsh brakings and avoid conflicts with other road users.

5. ASSESSMENT OF TIME SAVINGS THROUGH ASSISTED BODER-CROSSING SOLUTION

Early identification of low-risk traffic has been reported by The World Bank [33] as a way to improve queue management, and consequently, border performance. Furthermore, according to truck drivers' responses to a survey [34], the four most usual reasons of delays at border crossing points are:

- The required documentation: 33.4%.
- The custom agents' efficiency (change of shifts, breaks, waiting for other agents to come): 21.9%.
- Lack of necessary infrastructure and equipment: 21.3%.
- Congestion and waiting queues due to high traffic: 17.5%.

These findings indicate that there is demand for solutions for enhancing border processes.

The extended sensors user story was excluded from QoL assessment as its relevance from a traffic system perspective was considered low. However, enhancing border processes certainly has potential in reducing the waiting times of individual trucks at border crossings, and this is explored in this section as an example of potential benefits on a local or specific traveller group level. By enabling automatic information exchange for inspection of goods and documents, the efficiency of the border crossing processes can be increased. Furthermore, some potential improvements in border crossing processes are not dependent on the wide deployment of driving automation, and thus, related benefits could be achieved sooner.

Two scenarios related to the user story Extended sensors for assisted border-crossing are illustrated in Figure 26 and Figure 27. A more detailed description of the user story is presented in 5G-MOBIX Deliverable D2.1, pp.66-69 [35][3]. In short, risk classification of each incoming vehicle is performed utilizing AI and predictive analytics techniques and based on heterogeneous information ingested from vehicle On-Board Unit with connected sensors, Road-side Infrastructure and connected sensors and the neighbouring authorities. A vehicle that is assessed as "Low Risk" is instructed to proceed to "zero-touch" border crossing, where no human intervention is needed. Furthermore, the solution can monitor customs agents' locations and issue an alert and an instruction for a driver or a vehicle to stop or change course, if a safety risk is identified based on a vehicle's trajectory.

[3] A video on the use case can be viewed at https://www.youtube.com/watch?v=fRnY_jG3PoY.

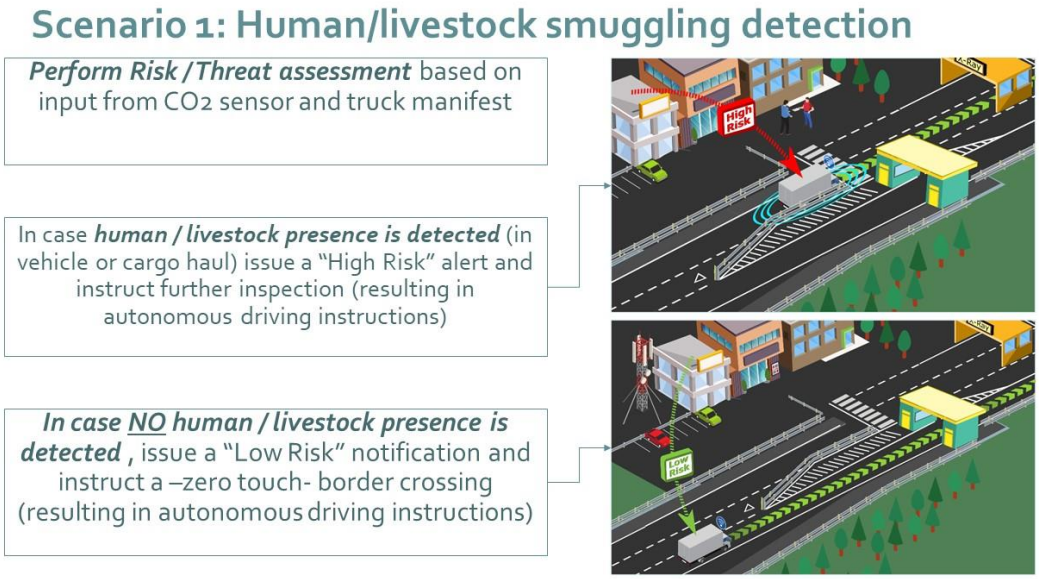


Figure 26: Assisted border-crossing, Scenario 1

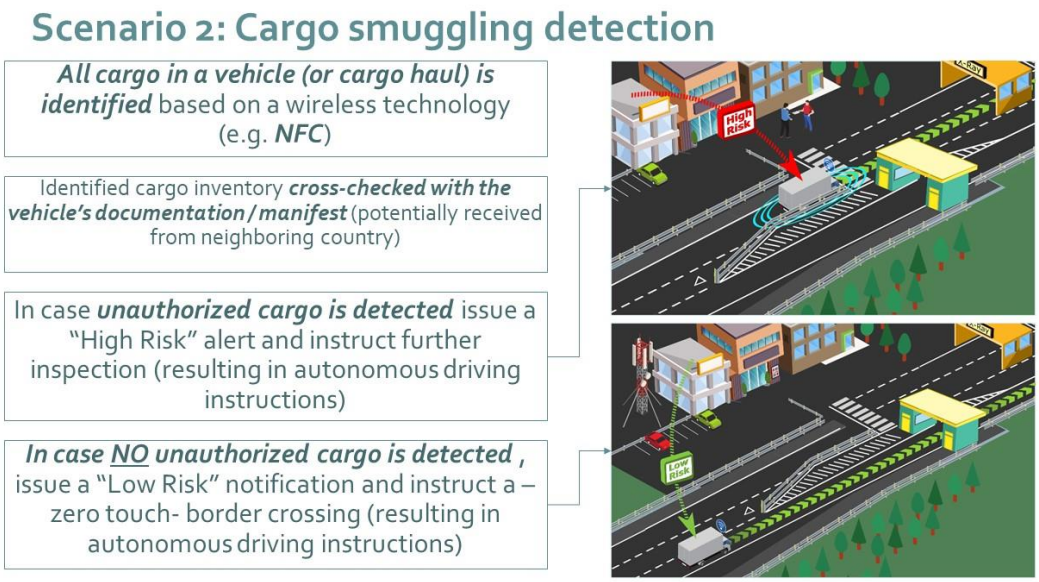


Figure 27: Assisted border-crossing, Scenario 2

In the following, the potential for time savings at the border-crossing has been studied for the vehicles that have been assessed as "Low Risk", and thus will be instructed to proceed to "zero-touch" border crossing.

The local authorities have estimated that at the GR-TR CBC the border crossing procedures including interaction with police and customs can at present take around 15 to 30 minutes per truck. In case further

checks are needed, the time can be even higher. This estimate is in line with the data on the border crossing times in South-East Europe reported by Miltiadou et al. (2017) [34]. It is expected that with the assisted border crossing system the customs process could be considerably shorter, and vehicles could pass the border with only a short stop (in the order of a couple of minutes). These estimates indicate that the time savings potential for individual trucks is large.

Numbers of trucks crossing the GR-TR border are available from statistics, however only on a yearly basis. It is not known how the arrival times at the border are distributed across a day or week, i.e. whether there are large peaks at certain hours and more quiet times at others. In the absence of such input information, uniformly distributing the numbers across days of a year and hours of a day results in about 11 trucks per hour on average crossing the border from each side (year 2022 statistics [4]).

Table 5. Number of trucks crossing the GR-TR/TR-GR border per year, day and hour

	Trucks	
	GR-TR	TR-GR
Trucks/year [4]	100291	93911
Trucks/day (avg)	274.8	257.3
Trucks/h (avg)	11.4	10.7

Assuming an average time saving of 15 minutes per truck, the total change would amount to an overall saving of 48500 hours per year, or 133 hours per day. An analysis on how these time savings would affect for example a logistics company, a truck driver and customs would require in-depth information of organisation of work, distances and routes of trips and frequencies of crossing the border. This type of company- and CBC-specific information was not collected in the study, but it can be assumed that time savings of this magnitude would be notable for several actors. Enhanced border processes and resulting decreased waiting times can be assumed to be especially significant during potential peak hours at the border, helping in avoiding queue build up.

The potential impacts of the enhanced border crossing on CO_2 are difficult to estimate, as the speed patterns are not known. Assuming that all trucks arriving at the border over a year could save on average 5 minutes of idling time, 63 tons of CO_2 could be saved. This value is reached by assuming 1.45 kg of diesel used per hour of idling [5] and 2.67 kg of CO2 per kg diesel. A study by Reyna et al. (2016) [36] assessed the potential changes in emissions at a border crossing between the USA and Mexico with traffic simulations

[4] Tır-Çekici-Dorse-Römork (Truck-Trailer-Trailer-Trailer), https://ticaret.gov.tr/data/61efa03313b876476cc9f9b0/Kara%20Kapilarina%20ve%20Arac%20Turlerine%20Gore%20Arac%20Sayilari..pdf

[5] https://dieselnet.com/tech/emissions_idle.php

and found that queue reduction through expedited procedures could, in a high congestion scenario, reduce CO_2eq emissions by up to 16% within the considered area (border inspection station and nine miles upstream). Similar benefits could probably be achieved with the assisted border crossing solution in the most congested times.

6. COST-BENEFIT ANALYSIS

The objective of this section is to study the societal benefits and costs that are expected to occur after the deployment of the additional infrastructure investment requirements for connected automated mobility in five European CBCs: Spain – Portugal (ES-PT), Greece – Turkey (GR-TR), Germany – Netherlands (DE-NL), Finland – Norway (FI-NO), Spain – France (ES-FR), in line with the CBCs included in the Deployment Study. While 5G-MOBIX is particularly focused on the CBCs ES-PT and GR-TR, the data available from the trials performed in the two corridors is insufficient to substantiate an evidence basis that could be used in an economic analysis. This results from the targeted scope of the trials (largely focused on the handover of the 5G connection) which was therefore inherently not focused on the inference of the socio-economic benefits resulting from changes in traffic behaviour (i.e. accelerations/decelerations, accidents, fuel consumption, etc.). However, the cost data collected for the Deployment Study, together with the joint analysis of different qualitative inputs, notably the assessment of impacts on Quality of Life, user acceptance and business models, enabled the comparability of costs and benefits, through a Cost-Benefit Analysis (CBA).

Cost-Benefit Analysis is a process of comparing the estimated costs and benefits of a project, programme, or policy, to verify analytically if these are worth pursuing and if they provide good value for money for society. Carrying out this analysis from the perspective of societal welfare involves including positive and negative externalities which are borne by society. It involves considering the broader social, economic, and environmental implications of an investment, beyond the immediate interests of the company or its stakeholders. Throughout this cost-benefit analysis the intent is to answer whether it is cost beneficial, from a societal welfare perspective, to invest specifically in 5G infrastructure that enables CAM services at border crossing areas compared to existing communications infrastructure, in view of a service continuity beyond the national borders. In other words, whether the quantified and monetised benefits outweigh or cover the costs of deployment. This analysis is subject to data availability constraints and the empirical findings of the project.

6.1. Existing evidence for 5G CAM

As part of considering a cost-benefit evaluation for the project, we conducted desk research to review the availability of costs and benefits on the use cases and other enabled services. The literature on 5G CAM in the context of CBCs is limited, with examples of cost-benefit analysis on 5G deployment and associated use cases in the context of road infrastructure, such as the report by Warwick Manufacturing Group (WMG) *Connected Autonomous Vehicles: Cost Benefit Considerations* [37], which does not consider CBC features. This project, along with others described hereafter utilises micro-simulation results, with limited verification in the real world. There are however a few EU-funded projects covering different angles of 5G applied to CCAM technology such as 5G CARMEN [15], 5GCRoCO [38].

5G NORMA [39] focuses on the development of the future 5G Mobile network architecture and is not specifically associated with mobility. As such, it does frame the implementation costs to a generalized

distribution of 5G, which is therefore not applicable for 5G-MOBIX. On the other hand, 5G NORMA does list the potential social benefits delivered by the improvements of existing wireless services and the introduction of new services, through the overall implementation of ITS via 5G technology, detailed in reduced carbon emissions, reduced congestions, and reduced road accidents (with associated fatalities and injuries). The 5G Norma report suggests (based on literature) that 5G adoption may lead to a reduction between 1% and 4%, in both travel time and greenhouse gas emissions, with estimated positive revenue from the onset of the deployment period, although the study doesn't address the cross-border specificities.

Along the same lines, another study funded by the European Commission [40] provides a forecast of the qualitative and quantitative socio-economic benefits of 5G, having a focus on transport (automotive vertical), smart cities, utilities, and health. The study suggested 5G capabilities will provide the following benefits (based on 2025 forecasts) across Europe:

1. In the Automotive vertical: €240.50 per vehicle per year, based on strategic and administrative benefits to manufacturers and consumers. Additionally, an operational benefit of €1.8 billion per year is forecast, based on an increase in vehicle sales of 1% due to the increased demand for new vehicles with 5G technologies.
2. In the Transport vertical, added value in 2025 of €153 per lorry based on improved telematics from the use of 5G). Additionally, an operational benefit of €3.2 billion per year is forecast, based on increased efficiencies / reduced empty loads.
3. A 5% reduction in road accidents, a 5% reduction in journey times, and a 3.5% reduction in CO_2.

These results are based on taking high-level industry forecasts for benefits and assuming a percentage of change can be attributable to 5G.

Moving towards similar contexts, 5GCroCo's [14] framework is somewhat closer to 5G-MOBIX and although the uses cases being analysed are not entirely comparable, there is a similar focus on cross-border sections. The project described the total costs for the infrastructure enabling CAM and its specific services, identifying that 5G coverage costs are approximately 13.5MM € per 100km based on an 8-year Total Cost of Ownership (TCO). On the benefits side, the project listed three main domains that provide an overall social benefit – vehicle technologies (ADAS, security, infotainment, and other driver assistance systems, such as Lane Keeping Assist, Lane Departure Warning, etc.), safer mobility, and cleaner mobility. They forecast a 90% penetration rate of connected technologies on new vehicles by 2022, representing benefits for the vehicle market of more than 180MM€. Given the 5GCroCo project's specific use-cases and assumptions, about 17% of potential accidents would be avoided. As for CO_2 emissions, figures between 1.1% to 9,5% reduction are suggested. The environmental results are based on a 5GAA report [41] which used both real world and simulated data.

5G-CARMEN [15] focused on cross-border 5G and CCAM use cases, concentrating on the cooperative manoeuvring and situation awareness scenarios. Decrease of number of road accidents and deaths and the

need to optimize fuel consumption are referred to as drivers for the solutions but estimates of benefits or assessment of societal impacts have not been reported (5G-CARMEN, 2022).

A report published by WMG as part of the UKCITE project produced modelled outputs for a series of use cases that can be enabled via connected and automated vehicles which are suited for the use of 5G [37]. The use cases studied are not quite the same as in 5G-MOBIX but comparable. Results are based on a baseline of less than 10% of vehicles equipped with connected and automated technology, with different scenarios for low, medium, and high adoption rates. The worst-case scenarios estimate at least a 1% improvement in safety benefits (ranging to 22% improvement in one use case). Improvements in journey times are positive, even if marginal, and CO_2 emissions are reduced as well (ranging from 0.19% to 4%).

As automated vehicles are enabled by 5G technologies, it is also important to examine a study considering the impact on travel time of automated vehicles. It suggested a 27% saving of travel time for Level 5 Automated Vehicles and 20% saving for Level 4 automated vehicles, assuming a 70% volume to capacity ratio and 100% penetration rate [42].

Another study considered the impact of 5% of a vehicle fleet being automated vehicles as a strategy to stabilise traffic flow and to dampen stop-go waves, an approach that is enabled using 5G technologies [43]. The study shows the emissions for all vehicles, not just the automated vehicles, and estimates a saving of up to 15% for CO_2 and 73% for NO during conditions where stop-go waves occur. The study also suggests benefits at other times but does not quantify these benefits.

One of the challenges around 5G is whether users are willing to pay for additional functionality. This study [44] conducted an online panel of 1260 individuals in the US who answered a vehicle purchase discrete choice experiment focused on energy efficiency and automated features. It found that an average household is willing to pay a significant amount for automation: about $3500 for partial automation and $4900 for full automation. Nevertheless, it should be noted that there was substantial heterogeneity in preferences for automation, where a significant share of the sample is willing to pay above $10,000 for full automation while many are not willing to pay any positive amount.

Overall, the literature review suggests some benefits can be delivered by 5G technology in road transportation or CAM, in relation with better traffic flow, increased road safety, and decreased CO_2 emissions. These findings are very much aligned with the benefits associated with ITS (particularly ITS-G5), which suggests that both technologies might potentiate each other.

The analysis we have found suggests that the use of CAM services can in specific conditions provide benefits to journey time, reduce delays and reduce emissions. There is variation in the level of benefits predicted but most of the studies suggest up to 10% benefits and possibly higher levels in specific circumstances. However, caution needs to be taken with these results as they have had very limited real-world validation.

6.2. Methodology of choice

As per the 5G-MOBIX deliverable D5.1 on the evaluation methodology and plan, the proposed approach was to undertake a cost-benefit analysis which expected to rely on the economic and financial analysis of the 5G-MOBIX x-border pilot cases, which is to say the benefits, the revenues therein, and the costs. As previously mentioned, the CBA seeks to compare monetised costs with benefits, through a ratio.

Another approach articulated in the deliverable D5.1 was Cost-Effectiveness Analysis (CEA), as an alternative to cost-benefit analysis, that could be used when benefits are of difficult monetisation, since CEA involves using a modified formula to CBA that does not require full benefit monetisation, but focuses instead on a measure of "effectiveness" in the numerator. A known challenge of using this method is that it usually focuses on one specific domain of benefits per cost-effectiveness ratio, instead of taking into account a whole range of quantified domains of benefits as enabled by the standard CBA.

The process for selection of the appropriate methodological approach is conditioned by the overall availability of the necessary data for such an approach. As illustrated by the CBA formula:

$$\frac{Total\ Benefits}{Total\ Costs} = CBA$$

Both benefits and costs need to be fully quantified. Below follows a visualisation of the CBA formula, in the context of a 5G-MOBIX -consistent deployment:

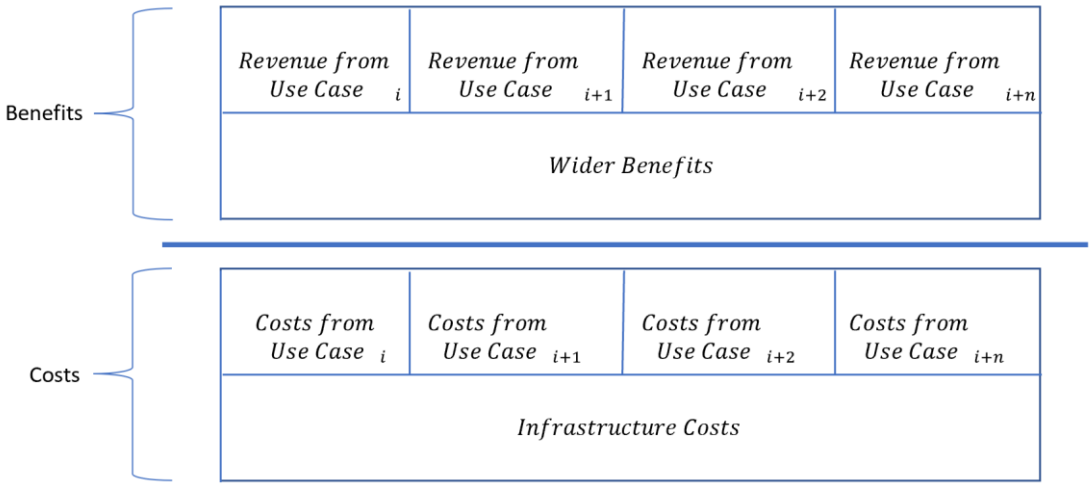


Figure 28: Simplified representation of a Cost-Benefit Ratio

As per the numerator in Figure 28, the benefits can be broken down between the revenues from use cases and wider benefits:

- **Revenues** from use case deployment were studied in the deliverable 6.2, albeit not quantified. These correspond to the sum of the stakeholder-level revenue generated because of each of the deployed use

cases. These would include cross-border applicable CAM-enabled use cases, such as infotainment or security.

- **Wider benefits** correspond to the benefits for society that go beyond revenue benefits. Some of these benefits are discussed in section 6.4. The full quantification of wider benefits for the use cases was not in scope for 5G-MOBIX deliverables, which measured and studied the technical variables associated with the aforementioned use cases, in terms of connectivity. Moreover, the wider benefits are mostly within the realm of a reduction in negative externalities: a reduction of the external costs generated by stakeholders, namely drivers, but that affect the wider society.

Similarly, the costs can be divided between:

- **Use case costs** represent the other side of the previously mentioned use case revenues. These costs correspond to all stakeholder-level costs incurred for the deployment of use cases, excluding any of the cross-use case infrastructure costs mentioned below. An example of this type of cost is the instalment of on-board units or sensors to enable CAM services. The Deployment Study assumed a level of uptake of fitted vehicles and that was what was used to derive the infrastructure need. However, it did not estimate the specific costs of these use cases.

- **Infrastructure costs** were identified and studied by the Deployment Study. These constitute the underlying infrastructure, without which the use cases could not be deployed. Moreover, these cannot be isolated, from one use case to another, as they allow the provision of a full array of services, and they amount to a full array of CAPEX (e.g. hardware installation, antennas, base stations, and fibre) and OPEX costs (e.g. site rentals, maintenance fees, annual software licences). It is worth highlighting that the infrastructure costs do not represent the full costs of infrastructure deployment, but rather the variation (i.e. delta) that captures the investment gap between the expected demand for 5G services that would enable the CAM use case services and the planned upgrades by either the agenda or regulatory obligations of the MNOs in the region.

As presented further down in section 6.5, there is some evidence of positive revenue expectations, from stakeholders. These aggregate revenues are therefore assumed to (at least) cover the use case costs so that they are breaking even in the use case deployment. So, to evaluate how cost-beneficial 5G deployment is in enabling CAM along CBC corridors, the wider benefits need to at least outweigh the infrastructure costs.

The question the CBA is therefore conditioned to respond to is "how high do the wider benefits have to be in order to justify the forecasted infrastructure costs". Within the CBA framework, the specific approach followed is a break-even analysis that is described in more detail in the following section.

The usual CBA approach involves defining a counterfactual, the scenario describing what would happen in absence of any additional 5G CAM service deployment and underlying infrastructure investment, which we can designate as business-as-usual. In the approach hereby specified, one can identify a counterfactual

scenario as a scenario where no additional infrastructure delta investment is made. Therefore, a break-even cost-benefit analysis identifies the point (the break-even point) where the attributable benefits, resulting from deployment, equal the costs. These benefits and costs considered corresponds to the incremental values above and beyond the business-as-usual scenario. So, as long as the benefits outweigh the costs, the deployment scenario is a net improvement for society, relative to a business-as-usual scenario.

Break-even analysis, in the context of cost-benefit analysis, is a parametric assessment of benefits where the parameter values are selected to equate costs and benefits [45], as per the following section:

$$Total\ Benefits = Total\ Costs \text{ or } \frac{Total\ Benefits}{Total\ Costs} = 1$$

This type of break-even analysis is particularly used when either only some of the benefits or only some of the costs can be quantified, it is therefore deployed to infer the plausibility of a project having higher benefits than costs, despite the lack of information completeness. This lack of information completeness is also referred to as non-quantifiability [46]. This approach has been explored in the public policy literature by Aos (2015) [47], Ponomarenko, M., & Friedman, B. (2017) [48], and Sunstein (2013) [49].

Although the most common application of this model is typically associated with the provision of products or services as outputs, it can also be used for modelling the provision of benefits such as increased road safety (measured in improvements in accident figures), decreased CO_2 emissions or travel-time improvements, as to derive the minimum level of benefits required in order to cover the costs.

6.2.1. Scenarios

When looking at the investment options, we present four investment scenarios across different years (2023 or 2025) and different 5G bands (700MHz and 3500MHz). The scenarios were informed by the deployment study regarding the time-phasing, the 5G band, and the capacity requirements of each CBC. These scenarios have been summarised in Table 6.

Table 6: Four investment scenarios

Scenarios	ES-PT	GR-TR	DE-NL	FI-NO	ES-FR
Scenario A	2023 Investment: 700 MHz	2023 Investment: 700 MHz	2023 Investment: 3500 MHz	2023 Investment: 700 MHz	2023 Investment: 3500 MHz
Scenario B	2023 Investment: 3500 MHz	2023 Investment: 3500 MHz	2023 Investment: 3500 MHz	2023 Investment: 3500 MHz	2023 Investment: 3500 MHz
Scenario C	2025 Investment: 700 MHz	2025 Investment: 700 MHz	2025 Investment: 3500 MHz	2025 Investment: 700 MHz	2025 Investment: 3500 MHz

Scenario D	2025 Investment: 3500 MHz	2025 Investment: 3500 MHz	2025 Investment: 3500 MHz	2025 Investment: 3500 MHz	2025 Investment: 3500 MHz

Scenario A assumes all investments take place in 2023, with corridors ES-PT, GR-TR, and FI-NO all investing in 700MHz. This 5G Band has sufficient capacity in both 2023 and 2025 for these corridors. For the DE-NL corridor, we assume investment in 3500MHz, as the Deployment Study remarked that 700MHz will not meet the required capacity in 2023. For the ES-FR, we also assume an investment in 3500MHz as although 700MHz would meet the required capacity in 2023, it would not meet the required capacity in 2025, making an initial investment in 3500MHz more future-proof.

Scenario B assumes an investment in 3500MHz across all corridors in 2023. This investment will have higher costs in terms of capital and operational expenditure but is likely to be a relatively more future-proof option.

Scenarios C and D follow the same 5G band investments as Scenario A and B respectively, but with all investments taking place in 2025 and under the assumption that investment did not take place in 2023. This reflects the alternative option presented in the Deployment Study around a potential delayed investment.

6.2.2. Model assumptions

Below follows a list of model-specific assumptions used to undertake the cost-benefit analysis.

1. A 3 % social discount rate has been applied, in line with European Commission guidance. The guidance states that member states are free to establish and use their own discount rate, with 3% being used in the absence of a national approach.

2. Historical inflation rates and forecasts derived from the respective country's central bank and other economic forecasts publications were used (with most countries having a 2023-24 forecast). Future years were estimated based on the ECB 2% inflation target6. The figures are displayed at 2022 constant prices.

3. Despite the long-term perspective principles laid out in Sartori et al. (2014) [52] the benefits realisation period considered, is 2023-2030 or the 2025-2035 period, the time interval where most benefits are expected to accrue, since it is challenging to forecast the appropriateness of the 700 MHz and 3500 MHz, many years into the future, given the deployment scenarios considered.

4. The cost-benefit break-even calculation considers the benefits to correspond to a decrease in the negative externalities, represented by the Handbook on the External Costs of Transport by Essen et al. (2019) [53], based on the total vehicle km per year.

[6] The 2022 macroeconomic environment has, thus far, been characterised by an increase in current and future-expected inflation, due to supply chain disruptions, geopolitical uncertainty, and the covid-19 pandemic.

6.2.2.1. Assumptions on Costs

The Deployment Study only considered infrastructure costs and did not cover the cost of equipment on vehicles such as on-board units. There was some suggestion of costs for on-board units that were listed because of a discussion with a truck manufacturer. The CBA model does not include them, as it is assumed that these costs are covered by the purchaser or vehicle manufacturer. It also reflects that the Deployment Study already assumes a level of up-take of connected and automated vehicles from 2024 which would already include the connectivity infrastructure.

The Deployment Study indicated that a margin of error of plus or minus 20% was possible on the costs. For simplicity in our analysis, we have used the costs without a margin of error and addressed this separately as part of the sensitivity analysis.

The Deployment Study assumed estimates for data usage/bandwidth for CAM vehicles, which determines the infrastructure to be deployed to provide sufficient capacity. There is significant uncertainty on the amount of data/bandwidth required by use cases, as it depends on how much data processing is carried out on the vehicle and how much data is processed in the cloud. There could also be secondary impacts, e.g. the introduction of CAM technologies might free up driver time to carry out other activities such as watching a film or working, which require additional bandwidth.

6.2.2.2. Assumptions on benefits

Given the constraints that arose along the process of building this economic analysis, the main assumption regarding benefits is that only externalities were considered. The benefits included in the model are those that approach the definition of public good, which is consistent with the assumption that government intervention happens to accelerate the rollout of 5G frequencies for CAM.

The externalities chosen were those available from the Handbook on the External Costs of Transport, Version 2019 – 1.1 [53]. It should be noted that externalities' costs refer to 2016 in the handbook and have thus been rebased. Externalities were chosen as most reflective of the likely impact of 5G-based use cases and those having a euro value per vehicle km. An EU28 average[7] value was used for the following externalities:

1. Climate change costs
2. Delay
3. Fatalities
4. Serious injuries

[7] The Handbook on the External Costs of Transport was written in 2019, before the UK left The EU, presenting average values of 28 EU nations.

5 Slight injuries

Climate change costs, which include CO_2 equivalent (CO_2e hereafter) emission savings as well as Well-To-Tank (WTT) emission savings, and delay costs were calculated against the modal splits for Passenger Vehicles, Transport Vans, Shuttle Buses, and Trucks. Safety benefits were applied to all vehicles. For safety-related benefits, the model assumes that the proportions of the different vehicle types remain consistent over time.

CO_2 equivalent is a metric widely used in emissions accounting and reporting and is used to compare emissions from various greenhouse gases based on their Global Warming Potential (GWP). Aggregating different greenhouse gases under a common metric - CO_2e - allows emissions, and in this instance costs of these emissions, to be reported under one metric.

For ease of analysis, the break-even calculation considers the externalities cost based on the total vehicle KM per year for the specific corridor for all vehicle types. Results are then presented as a percentage saving of this total figure for the relevant time period. This percentage is constant across externalities for each corridor. While these percentages are the same, in terms of absolute value these differ significantly across the different external costs, reflecting the differing value of reductions across external costs. These benefits are not necessarily applied across all vehicles, rather illustrating what percentage reduction in externalities would need to be attributed to the use of 5G-enabled CAM vehicles, services, and solutions to break-even.

Traffic volumes have been taken from the estimates in the Deployment Study model.

Baseline rates for fatalities, serious injuries, and slight injuries have been taken from national government statistics. For simplicity, accident rates are assumed to be the same either side of the border crossing and based on one country's statistics: GR-TR: Greece, ES-FR: France, FI-NO: Finland, ES-PT; Spain, DE-NL: Germany. Accident rates are either country averages for motorways or for the specific motorway (where available). For the ES-PT, DE-NL, and ES-FR corridors, statistics on slight injuries were not available and so this total external cost does not contribute towards the break-even percentages of these corridors. The base accident rate is assumed to remain consistent throughout the analysis period.

6.3. Costs

The costs listed in this economic analysis are derived from the information and assumptions determined in the 5G-MOBIX CAM Deployment study (summarised in 5G-MOBIX deliverable D6.5 [4]). Despite the underlying detailed costs being confidential, the costs in the final report have been utilised. These deployment study costs correspond to the 5G infrastructure delta in five European cross-border corridors, with this delta corresponding to the incremental investment above the currently planned investments that would deliver suitable coverage for the CAM use cases.

Within 5G-MOBIX there is only visibility into the costs of the 5G infrastructure delta and not the use-case or application-specific costs of deployment. However, some qualitative evidence was collected, as part of the

6.6 deliverable. Table 7 summarizes some of the responses, in terms of the stakeholder responses, from the Service Providers, MNOs, and OEMs on cost expectations.

Table 7: Expected impacts on costs for different stakeholders

	Service Providers	MNO	OEM
Staff costs	Negligible to Minor	Minor to Moderate	Moderate
Equipment and materials, including maintenance costs	Moderate to Significant	Significant	No data
Consulting / External services	Minor to Moderate	Moderate	Minor to Moderate
Network / Cloud / Hosting	Moderate	Significant to Major	Moderate to Significant
Patent / Sublicense	Moderate	Moderate to Significant	Moderate

6.3.1. Investment costs

The investment costs forecasted in the deployment study will be mainly contingent on what will be the deployment variation or "delta" between currently planned investments and existing infrastructure, and the necessary investments to deliver full coverage for the CAM use-cases. The main drivers for CAPEX differences seem to be (not exhaustively) associated with the current infrastructure level of installed technology and topography, as well as forecasts for road traffic intensity and vehicle adoption rate.

Those investment plans will, to a large extent, depend on the regulatory road coverage obligations. The implications of these regulatory obligations for MNOs and road operators are beyond the scope of this section, as the focus is on the expected costs for the deployment of the infrastructure needed to support specific use cases under analysis.

According to the Deployment Study, in relation to the investment costs required for 5G CAM deployment: "results indicate that required 5G (i.e., CAPEX) range from around 700k EUR in well-developed CBCs or those with low expected CAM traffic up to 3.7m EUR for those CBCs that are expected to require dense mid-band (3500 MHz) deployment due to high expected capacity demand from connected vehicles."

6.3.2. Operational costs

Operational costs are also described in the deployment study, specifically for the cross-border sections involved. Currently, none of these sections is properly covered by 5G service and strong enough to support

seamless CAM services. Operational costs (potentially not exhaustively) include software license fees per year, electricity costs, site rental fees, maintenance fees, and interconnection fees. The study inferred additional expected annual costs range from 62k EUR for the Spanish-French border and up to 909k EUR for the Finnish-Norwegian border.

6.4. Expected Benefits

The expected benefits are a consequence of the deployment and adoption of 5G automated use cases. The use cases referred to in section 6.1 are a sample of potential use cases enabled by this technology and not a comprehensive list of all the potential benefits.

The identification of benefits can be seen as flowing from Quality of Life (benefits) and Business-level impacts. From a quality-of-life perspective, the focus of this analysis involves establishing which impacts this technology has in mode choice, travel time, throughput, traffic safety, and emissions.

The QoL benefits are subdivided into the four areas below (detailed in Section 4):

1. Personal Mobility is associated with travel behaviour, choice of travel mode, and travel demand. The impacts of 5G in this area are expected to be very slim (at least for the use cases here analysed), hence representing negligible benefits.

2. Traffic Safety is a common and well-studied effect of ITS and C-ITS and well-established within the assessment of impacts on quality of life. Safety improvements are related to the risk, number, and severity of accidents, with 5G being expected to enable benefits through improvements in traffic safety.

3. Traffic efficiency is associated with traffic management, travel time, and the consequential hours lost. The implementation of 5G is expected to lead to efficiency improvements, even if small given the use cases studied in this context. It will most likely be easier to derive benefits for specific situations (like road works) than for overall usage.

4. Environmental impacts (namely greenhouse gas emissions, particle emissions, and noise) can be expected in any situation that alters mobility patterns and traffic efficiency. CO_2 emissions are strongly related to travel behaviour and traffic efficiency. Having expected benefits in traffic efficiency allows expectable improvements in CO_2 emissions due to less stop-start traffic but there could also be situations where increased speeds increase CO_2 emissions.

These quality-of-life expected impacts and benefits are aligned with the literature quoted in section 6.1 where the existing evidence for 5G CAM costs and benefits are analysed. These findings are also coherent with findings for ITS and C-ITS deployments (e.g. [50] and C-Roads Platform [51]).

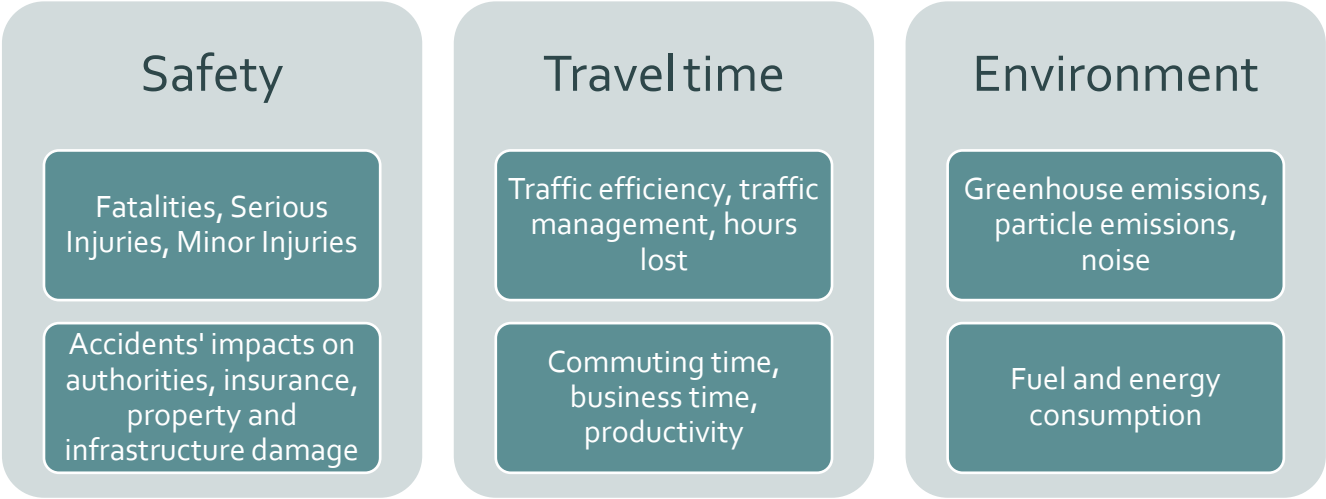


Figure 29: Areas of expected benefits in mobility and transportation of 5G deployment

6.5. Potential revenue sources

Questionnaires were conducted as part of 5G-MOBIX Work package 6, for stakeholders in and out of the consortia, aiming to capture information on business models including their impact on revenue and costs. Specifically, these questionnaires targeted vehicle OEMs, end customers, road operators, cloud and MEC providers, network equipment providers, and RSU providers. The questionnaire was focused on the deployment of 5G for the CAM services.

Stakeholders were also asked to evaluate the expected impact in revenue for their organisation as a result of the deployment of 5G for the listed CAM services for the next 10 years, under the assumption that 1=negligible, 2=minor, 3=moderate, 4=significant, 5=severe. As Figure 30 suggests (data collected from WP 6, deliverable 6.6), road operators are the most pessimistic considering possible incomes. They are quoted "having nothing that come to generate extra incomes".

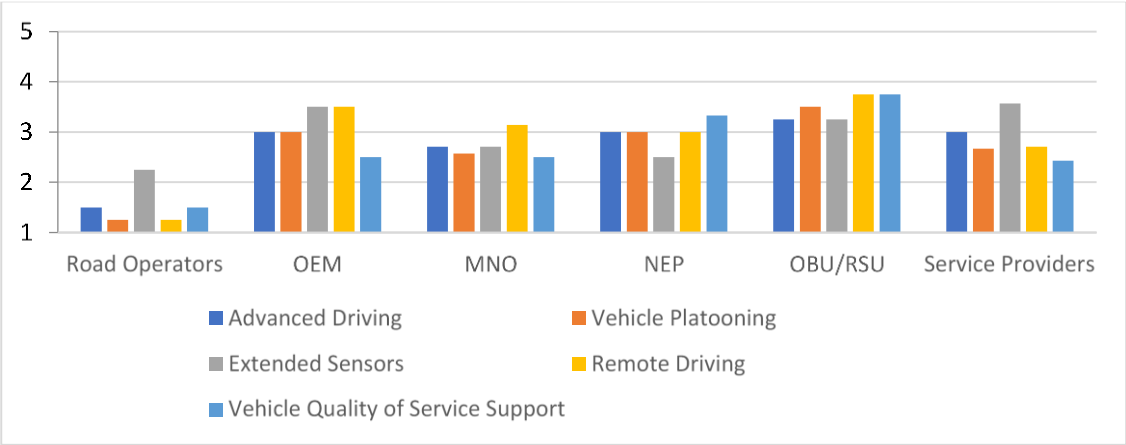


Figure 30: **Expected Impact on revenue per stakeholders' group**

Considering the services, they are quite balanced in terms of revenue generation, even if Vehicle Quality of Service Support is less prolific (Figure 31 - data collected from WP 6, deliverable 6.6).

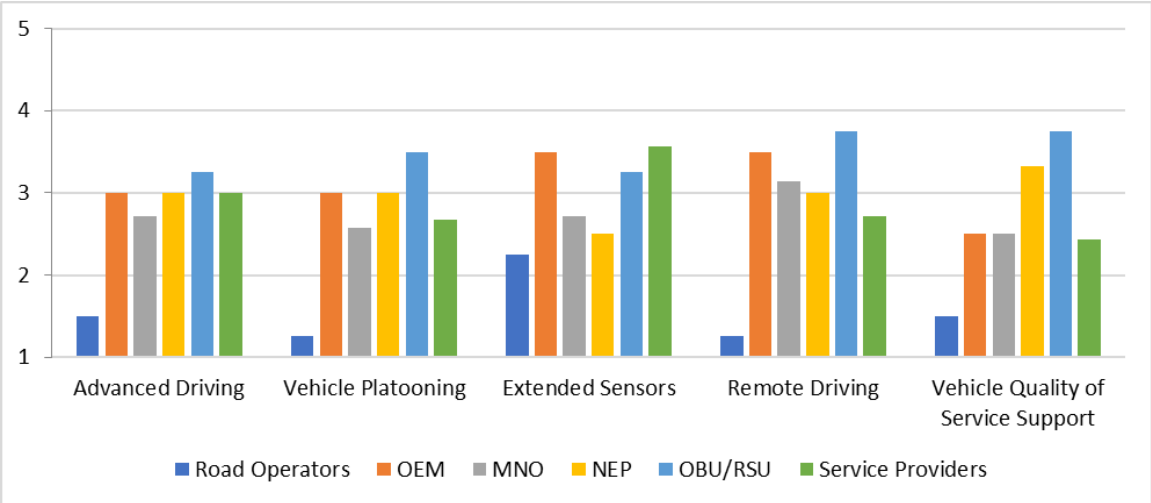


Figure 31: **Expected Impact on revenue per service**

From the end consumers' perspective, the same source of data seems to suggest that at least a third of respondents would have a positive willingness-to-pay, for an extra fee, for using the 5G-CAM services, although different preferences seem to arise depending on the use case being considered.

The findings on the stakeholder perspective on revenues provide positive support for the assumption that revenues may be large enough to offset the costs, however further quantitative empirical research is needed.

6.6. Results

6.6.1. Total External Costs

The total external costs represent the cumulative negative externalities incurred by society in a business-as-usual scenario, where no additional deployment of 5G CAM services is undertaken.

Scenarios A and B contain investments only made in 2023 and so the total external costs for these scenarios cover the time period between 2023 and 2030. These are summarised by corridor and externality in Table 8: Total External Costs in euros, 2023-2030. For scenarios C and D, the total external cost is calculated over a shorter date range, 2025 to 2030, due to the initial investment taking place in 2025 as can be seen in Table 9.

Table 8: Total External Costs in euros, 2023-2030

Total External Costs 2023-2030 (2022 constant prices in euros)						
Corridor	Fatalities External Cost (€)	Serious Accidents External Cost (€)	Slight Accidents External Cost (€)	CO2e External Cost (€)	Delay External Cost (€)	WTT Emissions External Cost (€)
ES-PT	27,406,182	409,027,436	N/A	53,490,040	45,112,122	17,237,305
GR-TR	5,481,441	5,570,813	321,836	6,752,797	5,667,655	2,187,303
DE-NL	26,483,106	188,214,699	N/A	110,567,869	95,048,677	36,002,719
FI-NO	1,033,031	238,897	171,860	1,797,283	1,510,807	582,364
ES-FR	28,875,958	45,880,315	N/A	110,087,009	93,220,862	35,513,686

Table 9. Total external costs in euros, 2025-2030

Total External Costs 2025-2030 (2022 constant prices in euros)						
Corridor	Fatalities External Cost (€)	Serious Accidents External Cost (€)	Slight Accidents External Cost (€)	CO2e External Cost (€)	Delay External Cost (€)	WTT Emissions External Cost (€)
ES-PT	20,146,481	300,679,003	N/A	39,320,912	33,162,245	12,671,267
GR-TR	4,094,607	4,161,367	240,409	5,044,302	4,233,707	1,633,903
DE-NL	19,467,922	138,357,975	N/A	81,279,234	69,870,964	26,465,857
FI-NO	787,754	182,175	131,055	1,374,609	1,154,827	445,363
ES-FR	21,226,924	33,726,949	N/A	80,925,750	68,527,324	26,106,365

6.6.2. Scenario Analysis

This section presents the percentage reduction required for each external cost in order to break even. This is broken down by corridor and by the scenarios presented previously in Table 6.

It must be noted that the FI-NO corridor does not appear in the tables below. This is due to a combination of low traffic volumes (around 500 vehicles a day in 2023) causing the total external costs in the tables above to be low in comparison to other corridors, and deployment costs to be high due to the topography of the region. Consequently, the externalities examined in the analysis alone do not justify investment in the FI-NO corridor for any of the proposed scenarios, i.e. a reduction in the negative externalities considered cannot be high enough to allow to offset the investment costs. This does not necessarily imply that investment in the FI-NO corridor is not cost-beneficial under any circumstance, as other non-monetised benefits could be considered.

As mentioned in section 6.2.2.2, the results of the analysis will be presented as a percentage reduction in the total cost of the aforementioned externalities that are required to break-even, over the relevant time period for each scenario.

Scenario A

Scenario A assumes an investment in 700MHz for the ES-PT, GR-TR, and FI-NO corridors, and 3500MHz in the DE-NL and ES-FR corridors with all investments taking place in 2023. ES-PT, DE-NL, and ES-FR are good options for investment, as even low levels of reduction in externalities (0.44% to 1.74%) would offset the infrastructure costs. This is consistent with the predicted benefits for CAM outlined in section 6.1.

GR-TR is likely to be a relatively more challenging case for investment based on externalities. It would require reductions in externalities close to 6%. This is possible and at the high end of the benefits suggested by the literature. However, the Deployment Study only assumed a 3% penetration rate for CAM on this corridor, so it may be challenging to achieve in practice with this low level of CAM vehicles.

Table 10: Scenario A, reductions in externalities to offset the investment

2023 to 2030	Cost (2022 constant, discounted)	Fatalities External Cost	Serious Accidents External Cost	Slight Accidents External Cost	CO2e External Cost	Delay External Cost	WTT Emissions
ES-PT	2,445,450.01 €	0.44%	0.44%	0.44%	0.44%	0.44%	0.44%
GR-TR	1,463,560.15 €	5.63%	5.63%	5.63%	5.63%	5.63%	5.63%
DE-NL	7,547,718.57 €	1.65%	1.65%	1.65%	1.65%	1.65%	1.65%
ES-FR	5,455,928.43 €	1.74%	1.74%	1.74%	1.74%	1.74%	1.74%

Scenario B

Scenario B assumes the deployment of 3500MHz infrastructure in all corridors in 2023. Note: there is no change in break-even percentages or costs from Scenario A for ES-FR and DE-NL corridors, where 3500MHz infrastructure is also assumed.

ES-PT, DE-NL, and ES-FR remain good options for investment as even low levels of reductions in externalities (1.11% to 1.74%) would offset the infrastructure costs and this is consistent with predicted benefits for CAM, even taking a pessimistic view of benefits.

GR-TR now requires just over 13% reductions in externalities, which makes the case even more demanding, in terms of the reductions to offset the costs, compared to Scenario A. The low predicted demand on this corridor could result in the lower-cost 700MHz option being pursued in practice.

Table 11: Scenario B, reductions in externalities to offset the investment

2023 to 2030	Cost (2022 constant, discounted)	Fatalities External Cost	Serious Accidents External Cost	Slight Accidents External Cost	CO2e External Cost	Delay External Cost	WTT Emissions
ES-PT	6,117,425.88 €	1.11%	1.11%	1.11%	1.11%	1.11%	1.11%
GR-TR	3,384,739.17 €	13.03%	13.03%	13.03%	13.03%	13.03%	13.03%
DE-NL	7,547,718.57 €	1.65%	1.65%	1.65%	1.65%	1.65%	1.65%
ES-FR	5,455,928.43 €	1.74%	1.74%	1.74%	1.74%	1.74%	1.74%

Scenario C

Scenario C is the same as Scenario A, but with the deployment deferred to 2025. There is limited difference between Scenario A and C, although the break-even percentages are slightly higher as there is less time for the benefits to accrue.

Our conclusions for Scenario C are similar to those of Scenario A, with ES-PT, DE-NL, and ES-FR all remaining good options for investment with only small reductions in externalities (0.45% to 1.99%) being enough to offset the infrastructure costs. These reductions are consistent with predicted benefits for CAM.

GR-TR remains to be a challenging case for investment based on externalities alone, with reductions of 6.14% required across externals costs. This is possible but is at the high end of the benefits suggested by the literature in section 6.1. However, as stated previously, the Deployment Study only assumed a 3% penetration rate for CAM on this corridor, so it may be challenging to achieve in practice with this low level of CAM vehicles.

Table 12: Scenario C, reductions in externalities to offset the investment

2025 to 2030	Cost (2022 constant, discounted)	Fatalities External Cost	Serious Accidents External Cost	Slight Accidents External Cost	CO2e External Cost	Delay External Cost	WTT Emissions
ES-PT	1,828,922.23 €	0.45%	0.45%	0.45%	0.45%	0.45%	0.45%
GR-TR	1,192,376.71 €	6.14%	6.14%	6.14 %	6.14%	6.14%	6.14%
DE-NL	6,354,750.08 €	1.89%	1.89%	1.89%	1.89%	1.89%	1.89%
ES-FR	4,584,960.72 €	1.99%	1.99%	1.99%	1.99%	1.99%	1.99%

Scenario D

Scenario D is the same as Scenario B but with the deployment deferred to 2025. There is limited difference between Scenario D and B, although the break-even percentages are slightly higher as there is less time for the benefits to accrue.

ES-PT, DE-NL, and ES-FR remain good options for investment as low levels of reductions in externalities (1.26% to 1.99%) would offset the infrastructure costs and this is consistent with predicted benefits for CAM, even taking a pessimistic view of benefits. GR-TR now requires close to 15% reductions in externalities, which makes the case even more marginal than in Scenario B. (Although the low predicted demand on this corridor means that the lower cost 700MHz option is likely to be pursued in practice).

Table 13: Scenario D, reductions in externalities to offset the investment

2025 to 2030	Cost (2022 constant, discounted)	Fatalities External Cost	Serious Accidents External Cost	Slight Accidents External Cost	CO2e External Cost	Delay External Cost	WTT Emissions
ES-PT	5,856,637.60 €	1.26%	1.26%	1.26%	1.26%	1.26%	1.26%
GR-TR	3,275,436.33 €	14.74%	14.74%	14.74%	14.74%	14.74%	14.74%
DE-NL	7,280,432.46 €	1.89%	1.89%	1.89%	1.89%	1.89%	1.89%
ES-FR	5,227,760.80 €	1.99%	1.99%	1.99%	1.99%	1.99%	1.99%

6.6.3. Sensitivity analysis

Sensitivity analysis, in the context of cost-benefit analysis, involves studying the response of the cost-benefit ratio to changes in input variables. The Deployment Study stresses that costs may vary by as much as ±20% within one country from operator to operator. This potential variation was used to inform part of the sensitivity analysis.

Due to the methods used to calculate the percentage reductions required to break even, the assumption that infrastructure costs could vary by ±20% corresponds with the percentage reduction of the total external cost also varying by ±20%. Naturally, this has an impact across all scenarios and all externalities, but with differing degrees across corridors. The increase and decrease in cost will have a larger impact on those corridors which have higher break-even percentages in comparison to those which have lower percentages. The ES-PT corridor has the lowest break-even percentages of all the corridors, and so ±20% in infrastructure costs do not change our conclusions made in the scenario analysis. Similarly, when varying infrastructure costs by ±20% for the DE-NL and ES-FR corridors, percentages remain feasible given the predicted benefits of 5G-enabled CAM vehicles and services with no change in our conclusions made in the scenario analysis.

The most significant impact of this section of the sensitivity analysis is on the GR-TR corridor, where break-even percentages are high across scenarios. The table below summarises the break-even percentages across all external costs, broken down by scenario as well as changes in infrastructure costs.

Table 14: Sensitivity analysis for the GR-TR CBC, by varying costs

GR-TR Corridor				
Break-even percentages	Scenario A	Scenario B	Scenario C	Scenario D
Original percentage	5.63%	13.03%	6.14%	14.74%
Assuming a 20% increase in cost	6.76%	15.63%	7.37%	17.68%
Assuming a 20% decrease in cost	4.51%	11.38%	5.37%	12.87%

From the table above it is clear that for the GR-TR corridor, scenarios B and D are unlikely to be cost-effective investments given that their break-even percentages are so high and above the predicted benefits for CAM vehicles, even with a 20% reduction in infrastructure costs. For scenarios A and C, which have an original break-even percentage across all external costs of 5.63% and 6.14% respectively, this variation in infrastructure costs can have a significant impact on break-even percentages. With the original break-even percentages being already at the top end of expected benefits for 5G-enabled CAM vehicles and services, an increase of 20% in infrastructure costs results in break-even percentages rising to 6.76% and 7.37% for scenarios A and C respectively, making them less likely to be cost-effective. The opposite effect occurs if infrastructure costs were to be up to 20% lower, with break-even percentages for scenarios A and C falling to 4.51% and 5.37% - still at the higher end of expected benefits from 5G-enabled CAM vehicles and services but more likely to be achievable.

As part of the sensitivity analysis, we also looked at removing some of the external costs from our calculations to check the robustness of our analysis, should one of the external costs not be reduced because of 5G-enabled CAM vehicles.

First, we looked at removing fatal accidents from the list of externalities. This was chosen due to the expected number of fatal accidents across all corridors ranging from 0.03-1.04 per year. This means that over the time period in question (either 2023-2030 or 2025-2030) there is a possibility that a fatal accident may not occur during this time in some corridors. When removing this external cost from our calculation and therefore assuming that 5G-enabled CAM vehicles will not impact fatal accidents over the 40km of motorway at each corridor, our assumptions stay largely consistent with those of a 20% increase in infrastructure costs; there no significant impact on corridors ES-PT, DE-NL and ES-FR and our conclusions stay the same as expressed in the scenario analysis, but for the GR-TR corridor the break-even percentage becomes less achievable, as illustrated in the table below.

Table 15. Sensitivity analysis for the GR-TR CBC, with the removal of the fatal accidents externality

GR-TR Corridor				
Break-even percentages	Scenario A	Scenario B	Scenario C	Scenario D
Original percentage	5.63%	13.03%	6.14%	14.74%
After removing fatal accidents from external costs	7.14%	16.51%	7.79%	18.68%

Lastly, we looked at removing both CO_2 equivalent savings as well at WTT emission savings as these two external costs are closely related. There are many considerations not yet accounted for when examining whether 5G-enabled CAM vehicles and services will lead to a reduction of CO_2e emission savings, and further research is required. It is not yet certain how the data processing needs of certain use cases will impact the emissions from automated vehicles and so as a robustness check, we remove external costs related to climate change, those being CO_2e savings and WTT emission savings.

Removal of these external costs will have the largest impact on break-even percentages for corridors with the highest traffic volumes and thus highest total external costs relating to climate change, those being the DE-NL and ES-FR corridors. In the scenarios presented above, these two corridors are recommended for investment in 3500MHz 5G bands, making the costs and therefore break-even percentages the same for scenarios A and B, and scenarios C and D. The effects of removing climate change external costs from these corridors, as well as the GR-TR corridor is presented in the table below.

Table 16: Sensitivity analysis for the DE-NL, ES-FR, and GR-TR CBCs, with the removal of climate change-related external costs

Break-even Percentages				
Corridor	Scenario A	Scenario B	Scenario C	Scenario D
Original percentage DE-NL	1.65%	1.65%	1.89%	1.89%
After removing climate change-related external costs	2.32%	2.32%	2.66%	2.66%
Original percentage ES-FR	1.74%	1.74%	1.98%	1.98%
After removing climate change-related external costs	2.95%	2.95%	3.37%	3.37%
Original percentage GR-TR	5.63%	13.03%	6.14%	14.74%
After removing climate change-related external costs	8.07%	18.67%	8.81%	21.12%

Removing the effects of climate change-related external costs has the largest effect on the DE-NL corridor followed by the ES-FR corridor. This makes the break-even percentages still within reach of the predicted benefits of 5G-enabled CAM vehicles, but a higher level of reduction across the remaining externals costs is required to break even.

Removing these external costs also increase break-even percentages significantly for the GR-TR corridor, the lowest of these being in scenario A at 8.07%. From the literature on CAM vehicles, it is unlikely that this level of reductions will be achievable, and therefore is unlikely to be a cost-effective investment should reductions in climate change costs not be realised.

6.7. Limitations

It should be stressed that the future estimates of inflation here presented do imply a considerable degree of uncertainty, due to the current supply chain disruptions, and the geopolitical and macroeconomic environment.

Although it was considered in the Deployment Study (and such assumption was transferred to this economic analysis) that the benefits could be considered immediately as soon as the costs were incurred (i.e. in 2023), this may not be the case with the full implementation of 5G technology. The full deployment of this sort of technology can be a matter for a long-term piece of analysis, in which the assumptions regarding fixed and variable costs don't hold. This could be a particular issue if use cases require new versions of the 3GPP 5G standards.

The relatively short timeframe of the analysis means there is no consideration of hardware or software technology refresh for 5G infrastructure.

The break-even analysis assumes that break-even percentages are the same across all external costs. While these percentages are the same, in terms of absolute value these differ significantly across the different external costs and therefore reflect the differing value of reductions across external costs.

The Deployment Study assumed relatively low proportions of CAM vehicles in 2023 (between 0.5 and 1.6% of total vehicles depending on Country) rising to 3% to 18% in 2030. The Deployment Study assumed this variation based on factors such as country GDP, age of vehicle fleet, and projections for CAM vehicle sales.

Even at the relatively low level of penetration rates, the literature we have found ([37], [43]) suggests that there are benefits applicable to the whole vehicle fleet. These benefits are assumed from simulation. However, there is limited knowledge of how human drivers would interact with significant proportions of CAM vehicles, especially if they behave differently to human-driven vehicles. Most of the literature assumes benefits such as a reduction in accidents and congestion. However, this depends on the uptake of CAM vehicles. There is a possibility that in the short-term additional accidents and delays are caused by human drivers not knowing or misunderstanding how driverless vehicles operate.

It may also be that benefits only accrue or are more significant during certain times for instance, during congestion or adverse weather conditions. The break-even analysis has not attempted to consider the nature or profile of traffic flows for each cross-border corridor.

Carbon emissions relate only to the emissions from vehicles and do not consider any emissions from data centres, processing, etc. Emissions per vehicle km are assumed to remain the same based on the external cost per vehicle km in the EU externalities handbook. This could change if there are significant changes to the vehicle fleet. Trends such as increasing vehicle size and electrification could change this.

7. INNOVATION ECOSYSTEM ANALYSIS

In this section we analyse advances towards future business in 5G enabled border crossing CAM solutions and ecosystem perspectives contributing to innovation activities. The advances towards future business have been analysed in terms of identification of customer need, evolution of business models, assessment of mature solutions entering the market, and development of capabilities within the ecosystem. In addition to the metrics above, we assessed a set of elements of an innovation ecosystem that have been identified as focal in literature, as introduced in D5.1 [5]. The innovation ecosystem perspectives are introduced in section 7.1.1. The perspective of this analysis differs from the objectives of the innovation management activities of the project, reported in D1.5 [54]: The innovation management activities focus on identifying the innovations emerging directly as a result of the project, but this analysis aims to analyse the elements that are relevant for sustaining innovation activities and continuous capability development, through co-creation and continued sharing of knowledge among ecosystem partners. The purpose of the innovation ecosystem analysis in this context is to highlight the factors that contribute to creating wider impacts in future, through the emergent technology. A well-orchestrated, sustainable and open innovation ecosystem is likely to support development of capabilities and innovations not only in the field of mobility but simultaneously in other fields as well. The research literature has brought up that efficient innovation ecosystems are not limited to the project activities but are expected to evolve and pursue exploitation of new knowledge in long term.

7.1. Methodology to analyse innovation ecosystem and progress towards commercial deployment

Some changes to the focus and approach of this analysis have been made, in comparison to the methodology presented in the deliverable D5.1. The methodology and the metrics were initially planned with the assumption that towards the end of the work, some promising cross border 5G for CAM business cases would have appeared. During the work it became apparent that the business cases and business models, and the clusters or ecosystems developing those, are still in early exploratory phases. Hence, a qualitative assessment of advances towards business opportunities according to the above-mentioned metrics was conducted, mainly based on the partners' outlook on exploitation, even if business cases for 5G enabled CAM services are not yet well developed. Furthermore, it was recognised that 5G-MOBIX T6.2 and T5.3 have synergies and they benefit from cooperation, but they take different viewpoints: T6.2 focused on business models and factors affecting those, including value networks related to the potential business cases, whereas the focus of innovation ecosystem analysis in T5.3 was on investigating elements to reinforce innovation activities, when relationships among actors are still co-evolving and business opportunities are being explored, and thus the interactions between the actors and their objectives differ from the business ecosystems or networks.

D6.5 [4] presents the deployment options and recommendations, as a result of a thorough analysis and prioritization process. Roles of the project partners and an outline of value networks and exchanges between the business network actors are presented in D6.2 [55]. Each stakeholder group's views on business models and value creation opportunities are presented in D6.6 [1]. The objective for conducting Multi-Actor Multi-Criteria Analysis (MAMCA) would have been similar to the WP6 activities, but would still require well developed descriptions of alternative business cases as a basis, and therefore the methodology was not applied.

The data collection in the form of workshops and discussions in parallel with other physical meetings didn't materialize due to the COVID-19 restrictions during the project, consequent delays and the hectic schedule to then conduct the trials and evaluation. This led to diminished opportunities to interact with the partners directly involved in 5G for CAM innovation and business development activities. To limit the number of parallel surveys, online meeting invitations and email requests to consortium members and other stakeholders to respond to, synergies in data collection were sought for. The main input data for this section are literature, the responses to the T6.2 stakeholder survey (D6.6 [1], section 5), T6.2 recommendation evaluation (D6.6 [1], section 4), D6.5 [4] sections 5 and 6 as well as the partners' outlook for exploitation of the results. T6.2 stakeholder questionnaires included also questions suggested by the T5.3 team for the purposes of cost-benefit analysis and innovation ecosystem analysis. The aforementioned data are here analysed to identify factors contributing to value co-creation and supporting innovation activities, having potentially long-term business impacts even if those cannot yet be clearly specified.

7.1.1. Innovation ecosystem characteristics and evaluation

The term innovation ecosystem and its conceptualisation has been increasingly discussed and investigated for more than a decade (see e.g. [56], [57], [58] and [59]). Innovation ecosystem has emerged as a promising approach in the literature on strategy, innovation and entrepreneurship [60]. However, different and even competing concepts of innovation ecosystem may confuse those interested in applying the approach, and hamper development of frameworks and methodologies for innovation ecosystem evaluation. In this study we refer to the following definitions for an innovation ecosystem:

- Adner (2006) [56](p.2) defines innovation ecosystems as collaborative arrangements through which firms combine their individual offerings into a coherent, customer-facing solution.
- Granstrand & Holgersson (2020) [59] describe innovation ecosystems as follows: "An innovation ecosystem is the evolving set of actors, activities, and artifacts, and the institutions and relations, including complementary and substitute relations, that are important for the innovative performance of an actor or a population of actors."

The concept of innovation ecosystem is especially helpful in the contexts characterised by future-orientation, where the current business model thinking needs to be widened from a single company point of view to an ecosystem perspective [60] and integration between the exploration of new knowledge and

its exploitation for value co-creation are pursued [61]. A summary of the differences between business, innovation and knowledge ecosystems is presented in Table 17 [61].

Table 17: Characteristics of ecosystem types

	Business ecosystem	Innovation ecosystem	Knowledge ecosystem
Baseline of ecosystem	Resource exploitation for customer value	Co-creation of innovation	Knowledge exploration
Relationships and connectivity	Global business relationships both competitive and co-operative	Geographically clustered actors, different levels of collaboration and openness	Decentralized and distributed knowledge nodes, synergies through knowledge exchange
Actors and Roles	Suppliers, customers, and focal companies as a core, other actors more loosely involved	Innovation policymakers, local intermediators, innovation brokers, and funding organizations	Research institutes, innovators and technology entrepreneurs serve as knowledge nodes
Logic of Action	A main actor that operates as a platform sharing resources, assets, and benefits or aggregates other actors together in the networked business operations	Geographically proximate actors interacting around hubs facilitated by intermediating actors	A large number of actors that are grouped around knowledge exchange or a central non-proprietary resource for the benefit of all actors

The differences between the ecosystem types imply that also different approaches to investigate and assess them should be employed. Further, de Vasconcelos Gomes et al. (2018) [62] suggest that innovation ecosystem is related to value creation while business ecosystem refers to value capture.

Despite the active research on innovation ecosystems, examples of systematic approaches for assessing evolution of innovation ecosystems and evaluating their business impacts to come are not easy to find in the scientific literature. Examples of evaluation approaches exist for national research agendas or programmes (see e.g. [63] and [64]), focusing dominantly on skills development and growth on national level. Evaluation of a service ecosystem was conducted in the NordicWay2 -project [65], but there the emphasis was on indicators related to business development, not on evaluating how the ecosystem contributed to co-innovation activities. Another stream of work focuses on identifying the key elements characterising efficient innovation ecosystems and developing guidelines for managing or orchestrating an innovation ecosystem (see e.g. [66] and [67]). Indeed, a **need for the ecosystem, shared vision and goals**, as well as **ecosystem facilitation** or orchestration models are frequently mentioned in literature as success criteria for well working innovation ecosystems. Furthermore, **openness** (or alternatively trust or willingness

to share knowledge) has been highlighted as a prerequisite for co-innovation. The 5G-MOBIX innovation ecosystem was analysed against these criteria, excluding however the ecosystem orchestration model.

A recent publication by Klimas and Czakon (2021) [68] presents a typology of innovation ecosystems, comprising of 14 typological criteria aggregated into five more general categories: 1) Life cycle, 2) Structure, 3) Innovation focus within Innovation Ecosystem, 4) Scope and 5) Performance. We also present a characterisation of 5G-MOBIX innovation ecosystem based on this typology. In the absence of a promising methodology to assess an innovation ecosystem, characterisation based on the typology provides a baseline description of the ecosystem and may support orchestration of the ecosystem in future.

7.2. Results

In this section, we first present the results of the assessment of the initially set metrics reflecting progress of the 5G enabled CAM towards commercial deployment: Customer need, Evolution of business models, Number of mature solutions entering the market and Development of capabilities within the ecosystem. Secondly, the results of the analysis against the applicable key criteria of an efficient innovation ecosystem are presented, followed by a characterisation of the 5G-MOBIX innovation ecosystem with the typology suggested by Klimas and Czakon (2021) [68].

7.2.1. Customer need

The stakeholder survey data (D6.6, section 5) indicates that end customers' and road operators' expectations on the benefits of the 5G for CAM solutions are mainly on improved safety. Several of the value propositions described in the business model analysis in D6.2 also focus on improved safety. Business cases on safety are however challenging to develop, since there should be credible evidence on safety impacts to motivate customers to pay for the solutions. In order to demonstrate the benefits through experimental data, infrastructure and services should be deployed in a setting corresponding to real life conditions with different types of vehicles and realistic traffic flows. Furthermore, assessment of the end-user acceptance and willingness to pay for business development purposes would require the overall concept to be defined, instead of specific separate use cases, to validate the feasibility of a business case.

Further, based on the results of the stakeholder survey for end customers (D6.6, section 5) it seems, that the most frequently experienced challenges with regard to mobility are unpredictability of travel time and lack of time. This could indicate that customer need exists for solutions that successfully target those issues.

Business model analysis in D6.2 also brought out opportunities for cost reductions for the transport and logistics sector, through decreased fuel or personnel costs, provided by the use case categories Vehicles Platooning and Remote Driving. Customer need for such value propositions can be assumed, even if those stakeholders were not engaged in validating this. Furthermore, potential improvements in traffic flows, resulting in time savings and possibly also decreased emissions, may be significant locally at the cross border

regions, and thus respond to the needs of public sector, even if at system level covering Europe as a whole the impact has been assessed negligible (see section 4.7).

5G-MOBIX has set the technological background that can allow the realisation of 5G for CAM business cases, but the market is only slowly emerging. Formulation of profitable business cases that respond to true customer needs requires further investigation and collaboration between stakeholders. 5G-MOBIX studied and demonstrated only few examples of border crossing applications building on the seamless connectivity provided by 5G. New innovative services to respond to diverse customer needs can be expected to be invented now that the capabilities and environments for developing and trialling are available.

7.2.2. Evolution of business models

As has been stated in the previous sections, the business cases for 5G enabled border crossing CAM services are not yet well developed and the market is only emerging. D6.2 presented analyses of initial business models for the 5G-MOBIX user stories. The described models were on quite generic level, focusing on identification of relevant stakeholder groups, their roles and describing the relations between the groups. The interests and challenges of different stakeholder groups were further analysed in D6.6. The results helped to identify potential conflicts and challenges as well as promising opportunities. These are essential preparatory steps in business design, but a detailed business model requires a viewpoint of a specified keystone organisation, specification of its resources, partners, channels and targeted customers, and thus this information is in general shared only internally in an organisation or with few trusted partners.

In order that a business model could be particularised, costs and revenues related to the business case need to be assessed. D6.5 section 4 presents the cost categories and summarises the cost data gathered in a literature review, but concludes that detailed economic information is challenging to find. As described in Section 6.5 potential revenue sources from the use cases and stakeholders' expectations were characterized in D6.2. D6.6 presents survey results on stakeholders' expectations on impacts on costs: Impacts on costs were assumed to be mostly minor to moderate by Service Providers and Automotive OEMs, but Mobile Network Operators expected impacts on costs to be mostly between moderate and significant. The number of responses to the stakeholder survey was however low, ranging between 3 and 11 responses per a stakeholder group, and several of the respondents did not respond to the questions on financial information, so these data cannot be regarded as representative. Quantitative cost information was not either obtained in the separate discussions with the consortium partners for the cost-benefit analysis. The challenges in collecting financial information potentially reflect the situation that development of business models is still in an early phase. An analysis of business models in D6.6, addressing costs and benefits of relevant stakeholders, and exploring the conditions for a feasible business case was conducted. Numerous assumptions were necessary to be made in the calculations, but nevertheless the results indicate that for some cases a win-win situation can be reached, especially if the costs of equipment will reduce in coming years.

In summary, specific evidence of evolvement of 5G for CAM business models could not be gained. Nevertheless, the efforts in 5G-MOBIX have resulted in improved knowledge of the barriers to deployment of 5G technologies for CAM and subsequent business, hence further clarifying the roles of partners as well as contributing to recognising the needs for coordination between different sectors. Actions are needed from multiple types of stakeholders, including standardisation and regulation bodies. In most cases, the business cases of various stakeholders are highly dependent of each other, which further increases the complexity and stresses the need for an ecosystem approach.

At the moment a chicken and egg problem seems to hinder development of business cases: Infrastructure and connectivity are needed before new customer-centric services start to emerge, making the investment cost-efficient, but the infrastructure is too expensive to build in case there is no demand in near future. Coordination of investments and through tender and auction processes helps to reduce lead times and investments, and thus supports progress towards defining and validating business cases, as highlighted by the recommendation R7 in D6.5. Similarly, the significant role of the public sector as a facilitator to emergent business, but also as a client and market driver, was also stressed in evaluation of the NordicWay2 ecosystem [65].

7.2.3. Number of mature solutions entering the market

In reference to the previous section on evolution of business models, 5G for CAM solutions are still in the development and trial phase. Research and development services and the trial sites capable of supporting advanced 5G enabled CAM functionalities currently constitute the main category of the offering that is mature for the market. The gained knowledge related to configuration and deployment of cross border 5G for CAM contributes to further development of technology but may also allow offering consulting services. Furthermore, some equipment and software vendors can refine their offerings available on the current market, based on the learnings from the project. For confidentiality reasons, the solutions or offerings are not specified here.

7.2.4. Development of capabilities within the ecosystem

5G-MOBIX trials provided a unique opportunity to test various protocols, scenarios and 5G features in the context of border crossing CAM, as well as to test the interoperability between different systems and components. The trials provided insights and lessons learnt not only on technological configurations, demands and capabilities but the work also resulted in improved knowledge on for example standards and regulations.

Here is a series of concrete cases of capability development that has occurred in the ecosystem, and that is assumed to have an impact on business on short to medium term, are given:

- Expertise on 5G On-Board-Units (OBU) and Road-Side Units (RSU) was developed through the trials with multiple kinds of devices and comparison of their performance in cross-border environments, as well as through the efforts to the tackle unexpected challenges along the way.

- Knowledge on current limitations to seamless roaming and cross network interconnection, providing valuable insight to mobile operators about future development needs and possibly also ideas for new functionalities.

- Fully equipped cross-border corridors and trial sites capable of supporting advanced 5G enabled CAM functionalities, and expertise on execution and preparation of tests at the sites. In addition to specific trials to support development, these capabilities also will enable validation in large scale pilots with growing number of CAVs in future. These are still needed for increasing trust in technology and to ensure reliable performance of the solutions in near operational conditions.

- Understanding of the most relevant barriers to deployment and business gaps that are significant for the whole ecosystem and cannot be tackled by individual organisations but require coordinated efforts. This knowledge has been refined into an extensive set of recommendations (see 5G-MOBIX deliverables 6.5-6.8).

The developed capabilities pave the way for future business in 5G for CAM, and simultaneously enhance the cooperation between stakeholders and nurture even further innovation activities.

7.2.5. Analysis of the innovation ecosystem

In this section, we analyse how the key components of an innovation ecosystem, providing an indication of evolvement of innovation capabilities and thus contributing to future business opportunities, have been reflected within 5G-MOBIX consortium and among related stakeholders. Lastly, we present a characterisation of the 5G-MOBIX innovation ecosystem.

7.2.5.1. Need for an ecosystem

The need for an ecosystem (or several ecosystems) has been a cornerstone for the project, and it has been frequently expressed in various terms, even if not explicitly always referred to as an innovation ecosystem. The vision of developing a CAM ecosystem in Europe needs to be supported by an ecosystem involving many different stakeholder communities. In addition, the results presented in the sections 7.2.1 - 7.2.4 indicate that an innovation ecosystem is needed to support integration between the exploration of new knowledge and its exploitation for value co-creation, as suggested in the literature, for future-oriented activities.

Within D6.6 [1], a recommendation concerning the need to cooperate for 5G deployment was studied. Indeed, when a cross-border infrastructure is planned, it must be agreed on how the costs, benefits and responsibilities will be divided between the respective parties to enable feasible operations for each of them.

Road operators, road authorities and mobile network operators should collaborate to create synergies for connectivity deployment along CAM corridors and cross borders, working together to develop end-to-end solutions for future mobility and transportation services. Stakeholders considered that this recommendation is important (3.6/5). Furthermore, during the project, importance of extending the ecosystem to include stakeholders representing additional verticals has been stressed.

Two other recommendations within D6.6 [1] concerned the pillars of the construction of an ecosystem: The creation of a Data Economy and the legislation underlying the ecosystem. Both recommendations are very important for the sustainability of the future of 5G-CAM services. Indeed, the 5G-enabled CAM data ecosystem and the smart infrastructures data ecosystems should merge in order to create the capacity to transform the economy by enabling third parties to create new data-driven services that will, combined with the two first data ecosystems, create a Data economy dedicated to 5G-enabled CAM IT services. As explained in the current work on "data spaces" within Gaia-X[8], the term "data space" refers to a type of data relationship between trusted partners who adhere to the same high-level standards and guidelines in relation to data storage and sharing within one or many vertical ecosystems. An innovation ecosystem that focuses on value creation and is open for cooperation is a way of initiating creation of data space. A current project PrepDSpace4Mobility [9] already aims to lay the foundation for a secured and controlled way of pooling and sharing mobility data across Europe and identifies existing European data ecosystems in the mobility and logistics sector..

Concerning the partnerships between the stakeholders of the ecosystem, the different actors in 5G-MOBIX have heterogeneous visions of its extent. Indeed, MNOs and OEMs describe the ecosystem in the broad sense, including Governments, Fleet owners, OEMs, OBU providers, Cloud/MEC providers, Road Operators, Network Equipment Providers and Software Solutions providers, whereas other stakeholders consider a smaller ecosystem.

This difference in scale of the ecosystem demonstrates its fragility and the need to further define the boundaries of the innovation ecosystem. It may also be necessary to articulate the concept of innovation ecosystem to all involved partners and to agree on the rules of the ecosystem.

7.2.5.2. Common vision and objectives

The document *5G Strategic Deployment Agenda for Connected and Automated Mobility in Europe*[10] presents a high-level vision and objectives concerning the 5G-deployment for Connected and Automated Mobility in Europe, building further on the targets set out in the *5G Action Plan for Europe*[11]. The underlying aim is to make Europe a world leader in Connected and Automated Mobility (CAM), leveraging the transformative potential of 5G. To support this aim, a target to achieve uninterrupted 5G coverage along all major transport

[8] https://gaia-x.eu/what-is-gaia-x/core-elements/data-spaces/
[9] PrepDSpace4Mobility (mobilitydataspace-csa.eu)
[10] https://5g-ppp.eu/wp-content/uploads/2020/10/20201002_5G_SDA_for_CAM_Final.pdf
[11] https://digital-strategy.ec.europa.eu/en/policies/5g-action-plan

paths by 2025 has been set. In this context, the benefits to be provided by CAM are envisioned: "*Fully automated driving promises to contribute to Vision Zero, by significantly reducing the risk of road accidents. It also promises to optimise vehicle flows and complex logistics and hence energy consumption on a large scale. Finally, the drivers becoming mere "passengers" will be able to devote their time to other activities, opening new economic possibilities such as transforming the vehicle into a mobile office space.*"

In addition to the high-level vision and objectives described above, 5G-MOBIX project naturally had the more specific goals that were shared among the partners involved in the project, and that steered the work and collaboration within the innovation ecosystem. In the context of development and configuration of technological solutions to enable advanced border crossing CAM use cases, and forming deployment related recommendations based on lessons learnt, the ecosystem coherently worked towards the shared vision. At the same time, understanding of the shared objectives significantly improved. However, there are indications about potential tensions within the ecosystem in more abstract aspects related to the common objectives, such as value creation opportunities as well as roles and responsibilities of the actors. This is reflected by the recommendation "Cooperate for 5G Deployment" in D6.6, emphasising the need for creating synergies and for developing end-to-end services. Furthermore, the results of the stakeholder survey (D6.6 [1]) indicate that especially the road operators do not see value in 5G for CAM. However, this result based only on four responses and thus would need to be further validated. The responses to the question about the most valuable border crossing 5G for CAM service were also scattered among the stakeholders, but that may reflect differences between the roles of stakeholders in a specific service. The use case Advanced driving seems to combine interests of several stakeholders (D6.6 section 5.2).

Lack of clarity of the vision and objectives in an innovation ecosystem may sometimes surface in form of passiveness or lack of commitment from some actors, not seeing significance of value co-creation. It can only be speculated if that was an underlying reason for the low number of respondents and quite large number of questions that were not responded to in the T6.2 stakeholder survey. Similar challenges were experienced also in efforts to engage stakeholders in discussions on costs and benefits and business cases. This further stresses the need to clarify the roles of the stakeholders in the ecosystem and to study potential incentives of each stakeholder for collaborating in the ecosystem. Improved understanding of customer needs, expected and potential benefits, cost structure and interests of potential partners in the stakeholder network are needed to refine joint objectives for the ecosystem, in order to strengthen the orientation towards exploring business opportunities. In that context, ecosystem objectives can be further aligned to increasingly respond to the high-level vision of 5G SDA, including reduction of road accidents and energy consumption.

7.2.5.3. Openness

In their study, Robertson, Caruana & Ferreira [69] demonstrate that the Knowledge-Based Dynamic Capabilities (KBDC) act as drivers of innovation performance in innovation ecosystems, across different market economies. Innovation ecosystems facilitate the flow of resources to transform ideas into reality. Moreover, it has been proven that "successful innovation ecosystems provide value by facilitating the flow

of information and providing access to resources, which assists with business cooperation and strategic innovation development beyond one's firm and industry borders" [68]. Therefore, a mature and sustainable innovation ecosystem requires openness between stakeholders in order to operate efficiently.

Knowledge gained in trials and during the preparations has been openly shared among the partners, but also in open webinars during the work. The sets of recommendations have also been developed as a joint effort, building on open discussions about barriers and challenges to be solved. It can be assumed that at an early stage, when business cases are not yet well developed, organisations' needs for cooperation still clearly exceed the need to promote potential future business interests in closed business ecosystems.

Furthermore, a recommendation concerning the need of openness between the ecosystem partners on some specific topics has been studied in the project. For illustration, for the recommendation Having Open Discussions About Machine Ethics, stakeholders considered that this recommendation is highly important (3.3/5) and must be addressed in the very short term (0.28/5).

7.2.5.4. Characterisation of the 5G-MOBIX innovation ecosystem

The typology suggested by Klimas and Czakon [68] was applied for characterizing the 5G-MOBIX Innovation Ecosystem (IE). The typology comprises of 14 typology criteria and options (types of innovation ecosystems) described for each of these. The number of options for each criterion ranges between 2 and 6, depending on the criterion. The criteria, types of IE, description of its characteristics and a reasoning for the selected option for 5G-MOBIX are presented in Table 18. Each selected option for 5G-MOBIX has been highlighted and marked with bold text in the table. The criteria category *Performance of innovation ecosystem* was not included in the characterisation of the 5G-MOBIX related innovation ecosystem, since at this early stage of development of the innovation ecosystem that cannot yet be addressed sufficiently in-detail (beyond the project focus).

Table 18: Typology of innovation ecosystems [68] and characterization of 5G-MOBIX

Criteria category	Typology criteria	Types of IE	Characteristics	5G-MOBIX related innovation ecosystem
Genesis and existence of innovation ecosystem	Ecosystem birth	**Intentional (deliberate, planned)**	**Purposefully created by focal firms or market players with above-average market power. The moment of an ecosystem's birth depends on the focal firm's decision**	5G-MOBIX project has been purposefully created by the consortium. However, abilities have been built during decades in various groupings and also earlier collaboration and the innovation ecosystem is not only for the project.
		Emergent (implicit)	**Emerging spontaneously. Non-intentional ecosystem emergence requires time counted in decades, thus it is hard to identify the moment of its birth**	

Criteria category	Typology criteria	Types of IE	Characteristics	5G-MOBIX related innovation ecosystem
	Governance mechanism	Orchestration (hierarchy)	The ecosystem is orchestrated by the dominant actor, usually a producer. Such type of IE is usually tightly and autonomously managed by the hub firm	
		Collectively coordinated (heterarchy)	Governance mechanisms are driven collectively by a set of actors—usually companies with access to strategic resources. Such a type of IE is usually loosely managed	
		Self-coordination	**The actors do not pay attention to ecosystem coordination. Such a type of IE is usually not managed but rather coordinated ad hoc**	Sustainable coordination of the ecosystem has not been that much in focus but is managed at large by project basis.
	Life cycle stage	Emerging	Ecosystems in the birth phase. In a more detailed view, this stage can be divided further into the preparation, formation and operation phases	
		Developmental	**Developing in terms of the number of actors engaged in co-realized innovation processes**	The number of engaged actors, their roles and ways to collaborate have not yet stabilised.
		Mature	Both the innovation ecosystem activity and its structure are stabilised, thus the dominant actors' behaviours are rather co-adaptative and co-evolutionary	
		Declining	The number of actors and innovation co-creation relationships decreases. The co-adaptative and co-evolutionary behaviours of actors get weaker. The focus of value creation is (if at all) paid rather to incremental innovations, while the co-innovation processes concentrate more on later stages	
		Death	The innovation ecosystem does not exist—some of the actors are operating on the market as they are trying to take the final benefits from collectively implemented innovation	

Criteria category	Typology criteria	Types of IE	Characteristics	5G-MOBIX related innovation ecosystem
			processes under the historic innovation ecosystem.	
Structure of innovation ecosystem	Actors	Symmetrical	Actors manifest a similar involvement in co-innovation processes	
		Asymmetrical	**Actors manifest a diversified involvement in co-innovation processes (e.g. corporate IE with the dominant engagement of private firms; university-based IE with the dominant engagement of universities)**	EC and public sector can be seen as a focal actor, but additionally engagement of research institutes and companies is required. The level of engagement of each actor varies depending on a topic.
		Centralized	There is a dominant actor (the focal firm) undertaking a leadership role, the essence of which is the orchestration of the innovation ecosystem	
		Decentralized	There is no dominant/focal actor	
	Innovation co-creation relationships	Ego-centric (firm-centric; hub-based)	IE considered from the perspective of the focal firm responsible for the product launch and its direct (one-way, bidirectional and multidirectional) innovation co-creation relationships maintained with other actors of IE	
		Eco-centric	**IE considered from the perspective of different actors and either their direct or indirect (one-way, bidirectional and multidirectional) innovation co-creative relationships with the companies responsible for the product launch**	Collaboration between actors and sectors is crucial and coordinated efforts are necessary (but need to be enhanced).
Leading innovation focus within innovation ecosystem	Innovation scope	Microscopic	The main focus is placed on the elements/implementation/outcomes of co-innovation, collaborative innovation or open innovation at the organisational level	
		Middlescopic	The main focus is placed on the elements/implementation/outcomes of co-innovation, collaborative innovation or open innovation at the industry/regional level	

Criteria category	Typology criteria	Types of IE	Characteristics	5G-MOBIX related innovation ecosystem
		Macroscopic	**The main focus is placed on the elements/implementation/outcomes of co-innovation, collaborative innovation or open innovation at the national/international level**	International networks have been established and collaboration and knowledge sharing takes place.
	Innovation type	Focused on disruptive innovation	Targeting market-breaking innovations (e.g. IE related to NASA)	
		Focused on radical innovation	**Targeting pure innovations based usually on new technologies**	Targeting innovations enabled by 5G, still at emergent phase.
		Focused on incremental innovation	Targeting innovations based on changes, adjustments or development of existing solutions	
		Focused on social innovation	Targeting social innovations focused on meeting social needs in a better way than before	
		Focused on path-breaking innovations	Targeting innovations breaking simultaneously current technology, market structure and the way of meeting social needs	
	Intensity of co-innovation process	Narrowed to co-Discovery	A priority importance of cooperation, a domination of exploitation of innovation co-creation relationships and the highest impact on value co-creation at the Discovery stage of the innovation process	
		Narrowed to co-Development	A priority importance of cooperation, a domination of exploitation of innovation co-creation relationships and the highest impact on value co-creation at the Development stage of the innovation process	
		Narrowed to co-Deployment	A priority importance of cooperation, a domination of exploitation of innovation co-creation relationships and the highest impact on value co-creation at the Deployment stage of the innovation process	

Criteria category	Typology criteria	Types of IE	Characteristics	5G-MOBIX related innovation ecosystem
		Narrowed to co-Delivery	A priority importance of cooperation, a domination of exploitation of innovation co-creation relationships and the highest impact on value co-creation at the Delivery stage of the innovation process	
		Narrowed to co-Dissemination	A priority importance of cooperation, a domination of exploitation of innovation co-creation relationships and the highest impact on value co-creation at the Dissemination stage of the innovation process	
		Adopting a multi-stage co-innovation focus	**Multi-stage cooperation across the innovation process, exploitation of innovation co-creation relationships at different stages of the innovation process, a dispersed process of value co-creation among different stages of the innovation process**	Co-deployment of 5G technology plays a major role in the ecosystem, but still in exploratory phase about the multifaceted opportunities enabled by it, and thus cooperation intersect all stages of the innovation process.
Range of innovation ecosystem	Technological scope	**High-tech**	**Operating around the industry (industries) classified as a high technology industry according to regulations developed by the OECD**	5G and CAM, data economy
		Medium-tech	Operating around the industry (industries) classified either as a medium–high or medium–low technology industry according to regulations developed by the OECD	
		Low-tech	Operating around the industry (industries) classified as a low technology industry according to regulations developed by the OECD	
		Mono-platform	Operating around one technological platform	
		Multi-platform	Operating around more than one technological platform	
	Spatial range	City-based/innovation districts	In the physical sense, the structure of IE does not extend beyond one city or industrial district. Usually, this type of	

Criteria category	Typology criteria	Types of IE	Characteristics	5G-MOBIX related innovation ecosystem
			ecosystem is led by municipal authorities	
		Local	In the physical sense the structure of IE is local	
		Regional	In the physical sense the structure of IE is regional	
		National	In the physical sense the structure of IE is national	
		International	**In the physical sense the structure of IE is international but not global**	Mainly bringing together European organisations and trials sites, but joint activities also outside of Europe.
		Global	In the physical sense the structure of IE is global	
	Physical scope	Digital (clicks only)	Operating only in cyberspace (e.g. IE related to blockchain technology, IE related to InnoCentive.com or other crowdfunding platforms). Among the digital innovation ecosystems are mobile digital ecosystems operating through mobile applications	
		Bricks & clicks	**Operating in both virtual and non-virtual reality**	Requires operation on both levels, focusing on development of data economy as well as physical environments for 5G for CAM solutions.

7.3. Concluding remarks on the innovation ecosystem analysis

Business development, requiring keystone companies with clear business interests to take a leading position, and co-innovation, where still exploration of value creation opportunities takes place, should be clearly distinguished as separate activities with differing objectives. Impact evaluation approaches should reflect the selected focus of the work. The challenge is that established methodologies for innovation ecosystem assessment do not yet exist.

Furthermore, systematic methodology for collecting data of the interactions and capability development in the ecosystem/consortium would be needed. In an ideal situation data collection would be less laborious

and with fewer opportunities to various interpretations than interviews and semi-structured workshops, which currently are generally used in data collection.

In a co-innovation phase emphasis should be put on coordination of the ecosystem activities, defining clear partner roles and exploration of incentives and value creation opportunities for all partners within the ecosystem (from single organisation point of view in business towards ecosystem perspectives). We suggest to include in future projects specific activities to support innovation ecosystem operations and evolution from the early phases of the project: Forming or validating a shared view and objectives, clarifying stakeholders' roles and expectations in the ecosystem (not just perspectives of organisations individually), and setting up measures to assess ecosystem evolution.

Structural barriers and challenges hindering development are often aimed to be identified in ecosystem analysis since those require a shared view and joint efforts among stakeholders. Those have been extensively covered in the 5G-MOBIX deliverables D6.5 - D6.8 and therefore were not discussed in this innovation ecosystem analysis.

8. CONCLUSIONS

The results obtained from the development and tests with the methodology for TTC assessment showcase the potential value that a method of overhead interpretation and analysis of traffic scenarios can provide. The trials in the project brought out areas where further development of the methodology is needed. Combining with the systematic approach that video analytics offers, this method can in future deliver insights into incident prone occurrences or areas in traffic, and allow for new technologies' impact on safety to be evaluated.

The quality of life impact assessment studied likely impact mechanisms of the 5G-MOBIX user scenarios in cross-border contexts on traffic safety, efficiency, the environment and personal mobility, in comparison with the baseline of connected automated driving with connectivity issues. The following impact mechanisms, through which 5G is expected to affect automated driving in cross-border context, were identified:

- Speed behaviour,
- Interaction with other vehicles and VRUs,
- Frequency of harsh braking and travelling reliability.

The anticipation of events enabled by 5G connectivity is expected to lead to avoiding takeovers and jerky trajectories, keeping a more constant speed, avoiding harsh brakings and avoiding conflicts with other road users. The user scenario with most effects is likely to be Lane merge and Automated overtaking.

Due to the lack of empirical information on 5G-enhanced automated driving, societal impacts on transport system level could not be quantified. Due to the specific nature of the user scenarios relating to cross-border contexts with limited geographical scale, and with low prevalence of those situations in the transport system or network, the impacts on traffic system level are likely small. Nevertheless, the QoL results are important in developing improved understanding on how new technologies and future services enabled by them may affect traffic system and society at large. Systematic analysis of the impact mechanisms and frequencies of effects contributes to identification of the most impactful services to affect mode choice, travel time and throughput, traffic safety and emissions. It can also be contemplated that even if this study focused on impacts in the limited cross-border context, the developed solutions may be essential to allow CAVs to roam through Europe, extending the geographical scale, and thus overall effect in traffic . Furthermore, travellers or drivers crossing the borders frequently may experience benefits, such as time savings and improved comfort. Sites with regular congestion or long queues caused by heavy vehicles may experience benefits locally. An illustrative example of the time saving potential was presented: A time saving of 15 minutes per vehicle crossing the GR-TR border was estimated to be possible to be reached through the user story *Extended sensors for Assisted border crossing,* when incoming vehicles will be classified based on the risk assessment, and "Low Risk" vehicles will be instructed to proceed to zero touch -border crossing. This can

be assumed to be significant on local level and for specific traveller groups, but societal impacts can also arise, assuming decreased idling time for the trucks crossing the border.

The Break-even analysis conducted as a part of the CBA studied what decrease in negative transport externalities (i.e. societal benefit) would cover the costs. The externalities considered were Fatalities, Serious Accidents, Slight Accidents, CO_2 Emissions, Delays and Well-to-tank. Through a vehicle-km calculation, the business-as-usual total external costs were calculated for the periods 2023-2030 and 2025-2030, which represent the expected costs in the absence of any interventions that would address these.

Four different deployment scenarios were considered, assuming different capacity requirements, bands and time-horizons. Illustratively, scenario A assumes investment in 700MHz for the ES-PT, GR-TR and FI-NO corridors, and 3500MHz in the DE-NL and ES-FR corridors, with all investments taking place in 2023.

The results from the different scenarios considered were relatively consistent. Taking scenario A as an example: The Greek-Turkish corridor is the only corridor (except for FI-NO) that would require a decrease in external costs of transport of up 5.63%, since all the other CBCs require reductions lower than 2%: 0.44% for ES-PT, 1.65% for DE-NL and 1.74% for ES-FR. These variations across countries are mainly due to lower traffic volumes (associated with lower population density), lower existing and planned development of RAN infrastructure and higher topography-induced costs, which is the case for the FI-NO CBC, with the results showing that the investment is not cost beneficial, from an externalities perspective, as a full reduction (close to 100%) in the monetised externalities considered, would not be enough to offset the infrastructure costs.

The results show that for all corridors, except the low-traffic FI-NO CBC, there is a good indication that CAM use-case deployment, across the four other CBCs considered could realistically allow offsetting the infrastructure costs considered. Even for the FI-NO CBC, there could be other non-monetised benefits associated with the investment, which make the investment cost beneficial even if it seems challenging to offset investment costs directly through reduction in externalities.

Discussion

All analyses presented in this deliverable provide indicative results, due to numerous assumptions and estimations that need to be made at this stage of development (no empirical data to support value proposition, and compositions of the market-ready solutions and services, affecting e.g. value proposition, pricing and costs structure, have not yet been defined).

The work in 5G-MOBIX focused on developing seamless connectivity to CAM enabled vehicles when crossing borders, and the scope of the impact assessment has been defined accordingly. However, the impacts of such solutions are likely to be clearly wider than the border crossing contexts, enhancing reliability and acceptability of CAM services overall, and thus promoting their uptake.

Confidentiality issues may hinder discussions about business actors' advances in business development. Also, information about cost structure of the products and CAM services is not available, partly due to that they are still under development but also for confidentiality issues. Those are anyway necessary for a proper CBA, in order to justify public investments that will then for one contribute to development of profitable business and promote competitiveness of European industries.

Innovation ecosystems, potentially aiming at disruptive solutions, may require different types of methodologies and metrics in assessment than more traditional product and service development projects. Co-development and co-learning are essential, whereas focusing on business model development (presenting a single company view) may impede collaboration. However, approaches for assessing innovation ecosystem and its impacts are not yet readily available.

REFERENCES

[1] 5G-MOBIX Consortium, "Deliverable D6.6 "Final report on the business models for cross border 5G deployment enabling CAM"," Available at https://www.5g-mobix.com/deliverables.

[2] 5G-MOBIX Consortium, "Deliverable D5.2 "Report on technical evaluation"," Available at: htpps://www.5g-mobix.com/deliverables.

[3] 5G-MOBIX Consortium, "Deliverable D5.4 "Report on user acceptance"," Available at: https://www.5g-mobix.com/deliverables.

[4] 5G-MOBIX Consortium, "Deliverable D6.5 "Final report on the deployment options for 5G technologies for CAM"," Available at: https://www5g-mobix.com/deliverables.

[5] 5G-MOBIX Consortium, "Deliverable D5.1 "Evaluation methodology and plan"," Available at: https://www.5g-mobix/deliverables.

[6] Aittoniemi, E., Barnard, Y., Harrison, G., de Klein, D., Kolarova, V., Lehtonen, E., Malin, F., Naendrup-Poell, L., Rämä, P. & Touliou, K., "Quality of Life Impact Assessment: AUTOPILOT Deliverable D4. 6," 2020. [Online]. Available: https://autopilot-project.eu/wp-content/uploads/sites/3/2020/09/AUTOPILOT-D4.6-Quality-of-Life-Impact-Assessment-v1.1.pdf. [Accessed August 2022].

[7] 5G-MOBIX Consortium, "Deliverable D4.3 Report on the corridor and trial site test activities," Available at: htpps://www.5g-mobix.com/deliverables, 2022.

[8] Mahmud, S. S., Ferreira, L., Hoque, M. S., & Tavassoli, A., "Application of proximal surrogate indicators for safety evaluation: A review of recent developments and research needs," in *IATSS research, 41(4), 153-163*, 2017.

[9] Bochkovskiy, A., Wang, C. Y., & Liao, H. Y. M, "Yolov4: Optimal speed and accuracy of object detection," arXiv preprint arXiv:2004.10934, 2020. [Online]. Available: https://doi.org/10.48550/arXiv.2004.10934. [Accessed August 2022].

[10] Innamaa, S., & Kuisma, S., "Key performance indicators for assessing the impacts of automation in road transportation: Results of the Trilateral key performance indicator survey," 2018. [Online]. Available: https://publications.vtt.fi/julkaisut/muut/2018/VTT-R-01054-18.pdf. [Accessed August 2022].

[11] Innamaa S., Smith S., Barnard Y., Rainville L., Rakoff H., Horiguchi R., Gellerman H., "Trilateral Impact Assessment Framework for Automation in Road Transportation. Version 2.0," Connected Automated Driving Europe, 2018. [Online]. Available: https://connectedautomateddriving.eu/wp-content/uploads/2018/03/Trilateral_IA_Framework_April2018.pdf. [Accessed August 2022].

[12] Kulmala, R., "Ex-ante assessment of the safety effects of intelligent transport systems, Accident Analysis & Prevention 42(4), 1359–1369," 2010.

[13] Malone, K., Hogema, J., Innamaa, S., Hausberger, S., Dippold, M., van Noort, M., de Feijter, E., Rämä, P., Aittoniemi, E., Benz, T., Enigk, H., Giosan, I., Gotschol, C., Gustafsson, D., Heinig, I., Katsaros, K., Neef, D., Ojeda, L., Schindhelm, R., Sütter, "Impact assessment and user perception of cooperative systems: DRIVE C2X Deliverable D11.4," European Commission EC, 2014.

[14] Vilajosana, X., Laaroussi, O., Via, S., Fischer, E., Hetzer, D., Bouillon, M., Coulet, F., Everingham, C., Schimpe, A., Rouma, D., Fernandez A.E., "Cost/Benefit Validation of Relevant 5GCroCo Business Potentials. 5GCroco Deliverable D5.2," 2021.

[15] 5G CARMEN, "5G CARMEN Deliverable 2.1 Use Cases and Requirements," 2020. [Online]. Available: https://5gcarmen.eu/wp-content/uploads/2020/03/5G_CARMEN_D2.1_FINAL.pdf.

[16] 5G-DRIVE Consortium (2018-2021), "Deliverables," Available at: https://5g-drive.eu/resources-and-results/project-deliverables/.

[17] 5.-S. P. Consortium, "The 5G-Safe Plus project," [Online]. Available: https://5gsafeplus.fmi.fi/index.

[18] Bjorvatn, A., Page, Y., Fahrenkrog, F., Weber, H., Aittoniemi, E., Heum, P., Lehtonen, E., Silla, A., Bärgman, J., Borrack, M., Innamaa, S., Itkonen, T., Malin, F., Pedersen, K., Schuldes, M., Sintonen, H., Streubel, T., Hagleitner, W., Hermitte, T., Hill, "L3Pilot Deliverable D7.4: Impact evaluation results," 2021. [Online]. Available: https://l3pilot.eu/fileadmin/user_upload/Downloads/Deliverables/Update_14102021/L3Pilot-SP7-D7.4-Impact_Evaluation_Results-v1.0-for_website.pdf. [Accessed August 2022].

[19] Rämä, P. & Kuisma, S. (Eds), "CARTRE D5.3 Societal impacts of automated driving," Available at: https://knowledge-base.connectedautomateddriving.eu/wp-content/uploads/2019/12/CARTRE_20180930_WP5_D5.3_Societal-impacts-of-automated-driving_V1.0.pdf, 2018.

[20] Innamaa, S., Axelson-Fisk, M., Borgarello, L., Brignolo, R., Guidotti, L., Martin Perez, O., Morris, A., Paglé, K., Rämä, A., Wallgren, P. & Will, D., "Impacts on Mobility – Results and Implications. Large Scale Collaborative Project TeleFOT, 7th Framework Programme, INFSO-ICT 224067," European Commission 2013 No: Deliverable D4.4.3, 2013.

[21] Aittoniemi, E., Rämä, P., Kuisma, S., Malin, F., Kahilaniemi, S., Mustaniemi, A., Coconea, L., Schünemann, B., Häusler, F., Ordinez, R., "Impacts of TEAM applications. Deliverable D5.5.1 of the TEAM project," 2016.

[22] Nilsson G., "Traffic safety dimensions and the power model to describe the effect of speed and safety," Bulletin 221, Department of Technology and Society, Lund University, Sweden, 2004.

[23] Do, W., Rouhani, O. M., & Miranda-Moreno, L., "Simulation-based connected and automated vehicle models on highway sections: a literature review," *Journal of Advanced Transportation,* 2019.

[24] Milakis, D., Van Arem, B., Van Wee, B., "Policy and society related implications of automated driving: A review of literature and directions for future research. Journal of Intelligent Transportation Systems: Technology, Planning, and Operations, 21(4), 324–348," 2017. [Online]. Available: https://doi.org/10.1080/15472450.2017.1291351. [Accessed August 2022].

[25] Taiebat, M., Brown, A. L., Safford, H. R., Qu, S., Xu, M., "A review on energy, environmental, and sustainability implications of connected and automated vehicles. Environmental Science and Technology, 52(20), 11449–11465," 2018. [Online]. Available: https://doi.org/10.1021/acs.est.8b00127. [Accessed August 2022].

[26] Shladover, S. E., Su, D., Lu, X. Y., "Impacts of cooperative adaptive cruise control on freeway traffic flow. Transportation Research Record, 2324(1), 63–70," 2012. [Online]. Available: https://doi.org/10.3141/2324-08.

[27] Papadoulis, A., Quddus, M., Imprialou, M., "Evaluating the safety impact of connected and autonomous vehicles on motorways," Accident Analysis & Prevention, 124, 12-22, 2019.

[28] Zhu, J., Tasic, I., "Safety analysis of freeway on-ramp merging with the presence of autonomous vehicles," Accident Analysis & Prevention, 152, 105966, 2021.

[29] Tafidis, P., Farah, H., Brijs, T., Pirdavani, A., "Safety implications of higher levels of automated vehicles: a scoping review," Transport Reviews, 42:2, 245-267, DOI: 10.1080/01441647.2021.1971794, 2022.

[30] Mattas, K., Makridis, M., Hallac, P., Raposo, M. A., Thiel, C., Toledo, T., Ciuffo, B., "Simulating deployment of connectivity and automation on the Antwerp ring road. IET Intelligent Transport Systems, 12(9), 1036–1044," 2018. [Online]. Available: https://doi.org/10.1049/iet-its.2018.5287.

[31] Shladover, S. E., "Opportunities and Challenges in Cooperative Road Vehicle Automation (preprint)," DOI 10.1109/OJITS.2021.3099976, IEEE Open Journal of Intelligent Transportation Systems, 2021.

[32] Bradford, J., Ajbulu, A., Chambers, C., Fletcher, S., Karousos, A., Konstantinou, K., Osman, H., Droste, H., Rendon Schneir, J., Zimmermann, G., Canto Palancar, R., Sciancalepore, V., Yousaf, Z., Rost, P., Doll, M., "Evaluation architecture design and socio-economic analysis – final report. Deliverable D2.3 of the 5G Norma project," 2017.

[33] McLinden, G., Fanta, E., Widdowson, D., & Doyle, T. (Eds.), "Border management modernization," World Bank Publications. Available at: https://documents1.worldbank.org/curated/en/986291468192549495/pdf/588450PUB0Bord101public10BOX353816B.pdf, 2010.

[34] M. Miltiadou, E. Bouhouras, S. Basbas, G. Mintsis ja C. Taxiltaris, "Analysis of border crossings in South East Europe and measures for their improvement," *Transportation Research Procedia,* nro 25, pp. 603-615, 2017.

[35] 5G-MOBIX Consortium, "Deliverable D2.1 5G-enabled CCAM use cases specifications," 2019.

[36] J. Reyna , S. Vadlamani, M. Chester ja Y. Lou, "Reducing emissions at land border crossings through queue reduction and expedited security processing," *Transportation Research Part D: Transport and Environment,* osa/vuosik. 49, nro December, pp. 219-230, 2016.

[37] Agca, A.O., Zafeiriadis, A., Godsell, J., "Cost-benefit Considerations To Enable A Connected Traffic Environment In The UK," 2016. [Online]. Available:

https://warwick.ac.uk/fac/sci/wmg/research/scip/reports/76010_wmg-cost_benefit-a4.pdf. [Accessed August 2022].

[38] Via, S., Fischer, E., Hetzer, F., Bouillon, M., Coulet, F., Everingham, C., Schimpe, A., Rouma, D., Fernandez, A.E., "Cost/Benefit Validation of Relevant 5GCroCo Business Potentials, report for 5GCroCo - Fifth Generation Cross-Border Control," 2021. [Online]. Available: https://5gcroco.eu/images/templates/rsvario/images/5GCroCo_D5_2.pdf. [Accessed August 2022].

[39] 5G NORMA, "Deliverable 2.3, Evaluation architecture design and socio-economic analysis – final report," 2017. [Online]. Available: https://www.it.uc3m.es/wnl/5gnorma/pdf/5g_norma_d2-3.pdf. [Accessed August 2022].

[40] European Commission, Directorate-General for Communications Networks, Content and Technology, "Identification and quantification of key socio-economic data to support strategic planning for the introduction of 5G in Europe: final report, European Commission," 2017. [Online]. Available: https://data.europa.eu/doi/10.2759/56657. [Accessed August 2022].

[41] Charoniti, E., Klunder, G., Schackmann, P.P., Schreuder, M., Schwartz, R.S., Spruijtenburg,D., Stelwagen, U., Wilmink, I., "Environmental Benefits of C-V2X for 5GAA, report for 5GAA C-V2X Environmental benefits," 2020. [Online]. Available: https://5gaa.org/wp-content/uploads/2020/11/Environmental-Benefits-of-C-V2X.pdf. [Accessed August 2022].

[42] Szimba, E., Hartmann, M., "Assessing travel time savings and user benefits of automated driving – A case study for a commuting relation, Transport Policy, Vol. 98, PP. 229-237," 2020. [Online]. Available: https://doi.org/10.1016/j.tranpol.2020.03.007. [Accessed August 2022].

[43] Stern, R.E., Chen, Y., Churchill, M., Wua, F., Monache, M.L.D., Piccolid, B., Seibold, B., Sprinkl, J., Work, D.B., "Quantifying air quality benefits resulting from few autonomous vehicles stabilizing traffic, Transportation Research Part D: Transport and Environment, Vol. 67, pp 351-365," 2019. [Online]. Available: https://doi.org/10.1016/j.trd.2018.12.008. [Accessed August 2022].

[44] Daziano,R.A., Sarrias, M., Leard, B., "Are consumers willing to pay to let cars drive for them? Analyzing response to autonomous vehicles, Transportation Research Part C: Emerging Technologies, Vol. 78, pp 150-164," 2017. [Online]. Available: https://doi.org/10.1016/j.trc.2017.03.003. [Accessed August 2022].

[45] Sassone, P.G., "Cost Benefit Analysis of Information Systems: a Survey of Methodologies, ACM SIGOIS Bulletin Vol. 9, Issue 2-3, pp 126–133," 1988. [Online]. Available: https://doi.org/10.1145/966861.45424. [Accessed August 2022].

[46] Heinzerling, L., "Quality Control: A Reply to Professor Sunstein, California Law Review, Vol. 102, pp 1457, 1468," 2014. [Online]. Available: https://www.jstor.org/stable/24758174. [Accessed August 2022].

[47] Aos, S., "What Is the Bottom Line? Criminology & Public Policy, 14(4), 633–638," 2015. [Online]. Available: https://doi.org:10.1111/1745-9133.12164.

[48] Ponomarenko, M., & Friedman, B., "Democratic accountability and policing. Reforming criminal justice: A report of the Academy for Justice on bridging the gap between scholarship and reform, 2, 5-26," 2017.

[49] Sunstein, Cass R., "The Real World of Cost-Benefit Analysis: Thirty-Six Questions (and Almost as Many Answers). Harvard Public Law Working Paper No. 13-11," 10 January 2013. [Online]. Available: https://ssrn.com/abstract=2199112 or http://dx.doi.org/10.2139/ssrn.2199112. [Accessed August 2022].

[50] Tsamis, A., Gibson, G., Biedka, M., Löhr, E., Levin, S., Figg, H., & Skinner, I., "Support study for the ex-post evaluation of the ITS Directive 2010/40/EU. Final report Study contract no (Vol. 4, pp. 2016-237). MOVE," 2018. [Online]. Available: https://data.europa.eu/doi/10.2832/254167. [Accessed August 2022].

[51] C-Roads Platform, www.c-roads.eu, "C-ITS Platform, Final report Phase II," September 2017. [Online]. Available: https://transport.ec.europa.eu/system/files/2017-09/2017-09-c-its-platform-final-report.pdf. [Accessed August 2022].

[52] Sartori, Davide, et al., "Guide to cost-benefit analysis of investment projects. Economic appraisal tool for cohesion policy 2014-2020," 2014. [Online]. Available: https://ec.europa.eu/regional_policy/sources/docgener/studies/pdf/cba_guide.pdf. [Accessed August 2022].

[53] Essen, H., Fiorello, D., El Beyrouty, K., et al., "Handbook on the external costs of transport : version 2019 – 1.1, Publications Office. European Commission, Directorate-General for Mobility and Transport," 220. [Online]. Available: https://data.europa.eu/doi/10.2832/51388. [Accessed August 2022].

[54] 5G-MOBIX Consortium, "Delverable D1.5 Innovation management Report," Available at: https://www5gmobix., 2023.

[55] 5G-MOBIX Consortium, "Deliverable D6.2 "Plan and preliminary report on the business models for cross border 5G deployment enabling CCAM"," [Online]. Available: https://www5g-mobix.com/deliverables. [Accessed August 2022].

[56] Adner, R., "Match your innovation strategy to your innovation ecosystem," Harvard business review, 84(4), 98, 2006.

[57] Ritala, P., & Almpanopoulou, A., "In defense of 'eco'in innovation ecosystem," Technovation, 60, 39-42, 2017.

[58] Ketonen-Oksi, S., & Valkokari, K., "Innovation ecosystems as structures for value co-creation," Technology Innovation Management Review, 9(2), 2019.

[59] Granstrand, O., & Holgersson, M., "Innovation ecosystems: A conceptual review and a new definition," Technovation, 90, 102098, 2020.

[60] Leminen Seppo, Rajahonka Mervi, Westerlund Mika, Wendelin Robert, ""The future of the Internet of Things: toward heterarchical ecosystems and service business models", Journal of Business &

Industrial Marketing, Vol. 33 Issue: 6, pp.749-767," 2018. [Online]. Available: https://doi.org/10.1108/JBIM-10-2015-0206. [Accessed August 2022].

[61] Valkokari, K., "Business, innovation, and knowledge ecosystems: How they differ and how to survive and thrive within them," Technology innovation management review, 5(8), 2015.

[62] de Vasconcelos Gomes, L. A., Facin, A. L. F., Salerno, M. S., & Ikenami, R. K., "Unpacking the innovation ecosystem construct: Evolution, gaps and trends," Technological forecasting and social change, 136, 30-48, 2018.

[63] Ministry of Economic Affairs and Employment, "National Growth Programme for the Transport Sector 2018-2022. MEE Guides and other publications 1/2018," 2018. [Online]. Available: http://julkaisut.valtioneuvosto.fi/bitstream/handle/10024/160721/1_2018_MEAE_guide_National_Growth_Programme_Transport_03042018.pdf. [Accessed August 2022].

[64] Sabatini Marques, J., Yigitcanlar, T., & da Costa, E. M., "Australian innovation ecosystem: A critical review of the national innovation support mechanisms," Asia Pacific Journal of Innovation and Entrepreneurship, 9(2), 3-28, 2015.

[65] Innamaa, S., Kulmala, R., Mononen, P., Penttinen, M., Tarkiainen, M., Baid, V., Bergqvist, D., Dörge, L., Hjälmdahl, M., Hökars, F., Kauvo, K., Malin, F., Meland, S., Pedersli, P. E., Rämä, P., Sannholm, M., Schirokoff, A., Simons, M., Ström, M., ... Öörn, "NordicWay 2 - Evaluation results," 2020. [Online]. Available: https://uploads-ssl.webflow.com/5c487d8f7febe4125879c2d8/5fdb176c20c0a29823b40c68_NordicWay%202%20Evaluation%20Report_FINAL.pdf. [Accessed August 2022].

[66] Rusanen, H., Makkonen, H., Paasi, J., Valkokari, K., & Laiho, T., "Modes of open innovation in ecosystems: Exploring for Managerial Playbook," In The ISPIM Innovation Conference: Innovating in Times of Crisis, Lappeenranta University of Technology, 2020.

[67] Valkokari, K., Valkokari, P., Rantala, T., & Nyblom, J., "Exploring the Best Practices for Co-innovation in Industry and Academy Collaboration–Four Practical Case Examples," In Working Conference on Virtual Enterprises (pp. 749-758). Springer, Cham, 2021, November.

[68] Klimas, P., & Czakon, W., "Species in the wild: a typology of innovation ecosystems," Review of Managerial Science, 1-34, 2021.

[69] Robertson, J., Caruana, A., & Ferreira, C., "Innovation performance: The effect of knowledge-based dynamic capabilities in cross-country innovation ecosystems," International Business Review, 101866, 2021.

[70] Rämä, P., & Koskinen, H., "Three driver and operator behaviour models in the context of automated driving: Identification of issues from human actor perspective. In Advances in Human Aspects of Transportation: Proceedings of the AHFE 2017 International Conference on Human Factors i," 2018. [Online]. Available: https://doi.org/10.1007/978-3-319-60441-1_100. [Accessed August 2022].

APPENDIX A: USE CASE CATEGORIES / USER SCENARIOS OVERVIEWS

The following table summarizes all UCCs and USs considered across the trial sites in 5G-MOBIX.

Table 19: 5G-MOBIX Use Case Categories and User Stories

Trial site	Advanced Driving	Vehicles Platooning	Extended Sensors	Remote Driving	Vehicle QoS Support
ES-PT	Complex manoeuvres in cross-border settings *Scenario 1: Lane merge for automated vehicles* *Scenario2: Automated Overtaking*		Complex manoeuvres in cross-border settings *Scenario3: HD maps*	Automated shuttle remote driving across borders *Scenario 2: Remote Control*	Public transport with HD media services and video surveillance
	Automated shuttle remote driving across borders *Scenario 1: Cooperative automated operation*		Public transport with HD media services and video surveillance		
GR-TR		Platooning with "see what I see" functionality in cross-border settings	Extended sensors for assisted border-crossing		
			Platooning with "see what I see" functionality in cross-border settings		
DE		eRSU-assisted platooning	EDM-enabled extended sensors with surround view generation		
FI			Extended sensors with redundant Edge processing	Remote driving in a redundant network environment	
FR[12]	Infrastructure-assisted advanced driving				

[12] Based on received feedback during the second technical review of 5G-MOBIX, VEDECOM has decided to only keep the infrastructure-assisted advanced driving use and withdraw the use case of remote driving. This decision came after the PO and reviewer's recommendation to concentrate efforts on 5G contributions and also to remove the police and security features since it's out of the scope of the project and their feedbacks on satellite communications. In this new specification of the user story, we will test two different approaches on how the infrastructure can assist advanced manoeuvres: the first phase will allow to carry out a MEC assisted lane change manoeuvre, while the second step will

NL	Cooperative Collision Avoidance		Extended sensors with CPM messages	Remote driving using 5G positioning	
CN	Cloud-assisted advanced driving	Cloud-assisted platooning		Remote driving with data ownership focus	
KR				Remote driving using mmWave communication	Tethering via Vehicle using mmWave communication

test a far-MEC approach (cloud-assisted) where the V2X application server will assist the lane change operation. This new design of the user story is different compared to what was already specified in previous deliverables (D2.1-D2.4) and is considered as an update of the FR site user stories. In addition, these changes will be reflected in the upcoming deliverables.

APPENDIX B: QUALITY OF LIFE IMPACT MECHANISM FRAMEWORK

1 Use of AD (Block 1)

a Acceptance

The acceptance of automated driving is linked to the intended acquisition of automated vehicles, specific functionalities or services, as well as their intended use. The user needs to have some knowledge (or at least a mental image, which may not be based on reality) of the automated functions to be able to accept them.

Automation awareness refers here, on one hand, to the user's general knowledge on the automated functionalities, their performance and limitations. The user needs to know of the operational design domain (ODD), i.e. in which driving environments and circumstances the vehicle can drive in automated mode.

Willingness and possibility to have indicates whether the potential user has the means, and whether they intend to acquire or choose (in case of car-sharing) automated functionalities into the car they use. As a mental resource, the potential user needs to have at least some general knowledge about automated functionalities to reliably indicate willingness to have.

Willingness to use is difficult to measure. To some extent it is reflected by actual use, i.e. the share of trips or km the user is willing to use the automation within its ODD; how frequently and in which circumstances the automated functionalities are used. The user may use the functionalities on all trips and in all conditions when the service is available (inside the ODD), or they may be willing to use the systems in specific conditions only, for example on long trips, on motorways or when tired.

b Transport system

Here, the transport system is outlined as *road* transport system.

Transport management refers to how the whole road transport system is managed; what infrastructure and vehicles are available and how they are controlled, what transport services are offered to the users in the city or other administrative area. Transport management is implemented on local, regional, national, European levels and also covers the relationships and cooperation of different levels.

Operation of vehicles / systems is part of the transport management referring how vehicle fleets - buses, shuttles, robotaxis, platoons of cars or trucks - are operated. It concerns questions such as who is the operator, what is the role of automation, which are the principles or rules of operation at different times of the day (week; other circumstances), are there any priorities, how is multimodality taken care of, etc.

Equipping vehicles with automated functionalities is reflected in the *price of AV*. Price formation of cars and vehicles is influenced also by other parallel changes such as electrification of road transport. Price is dependent on business models (who is going to pay and what, how the costs and profits are shared) and the price setting of AVs for example in car sharing.

Travel costs are formed for example of vehicle costs, moving power costs, leasing costs, ticket costs, parking cost and time costs. It has been suggested that the value of time is going to change with higher levels of automation allowing drivers in road transport to engage in other activities than vehicle operation.

2 Mileage per mode (*Block 2*)

a Vehicle operations

The category *Vehicle (control) operations* includes the driving behaviour of the AV itself, such as its acceleration, deceleration, lane keeping, car following, lane changing and gap acceptance. Vehicle operation characteristics (driving style) directly affect several other impact areas such as road (network) capacity and road safety. Relevant automation applications include those which provide longitudinal and/or lateral control with respect to the road and other vehicles [11].

Car following describes the longitudinal driving behaviour of the AV when following another vehicle, e.g. the time headway to the vehicle in front and its potential changes in time.

Lane keeping refers to the lateral behaviour of the AV, meaning how well it stays inside a lane and whether there are oscillations in lateral movement. *Lane changes* can be partly automated, initiated by the driver (with turn signal) or they can be (totally) automated, initiated by the AV when encountering a vehicle ahead travelling at a slower speed than targeted by the AV or when required to follow the route. In presence of other vehicles in the next lane, the AV needs to find suitable gap for the lane change (*gap acceptance* of the AV). Gap acceptance is relevant also for intersections where the AV needs to yield.

Speed behaviour describes the speed choice of the AV (target speed) and its potential changes in different situations (such as speed variation). There are several detailed indicators to describe speed behaviour such as spot speeds, mean speed, variance of speed.

Interaction with other vehicles and VRUs refers to all kinds of interactions between the AV and other road participants, such as over-takings, cut-ins, distance kept to other road-users, stopping behaviour at intersections and pedestrian crossings, gap formation at ramps, etc.

The category *safety manoeuvres* includes behaviour programmed into AVs for situations where the driver does not take back control when requested (minimum risk manoeuvres) as well as manoeuvres carried out by the driver, e.g. manual braking or steering if the AV does not seem to handle some situation.

The term *situational picture* refers to the interpretation of the situation around the vehicle (the current traffic situation, the road and the environmental conditions) formed on basis of the information available to the vehicle (or driver) from its sensors and via connectivity.

b AD User

The items under 'AD user' address the perspective and experience of the user and their change from being a driver (in manual driving) with increasing automation to being a user (in full automation).

'Ease of driving, non-driving' indicates driver experience/opinion on how easy it is to take care of all the dynamic and other driving tasks, but also the possibilities for doing other things than driving during the trip. Non-driving refers to the periods of time where the user does not need to drive, enabled by the AV taking control of the driving task. The length and frequency of non-driving periods are critical for ease of driving. AD may change the nature and extent of *in-car activities* carried out by the user while riding/driving. Ease of driving also refers to making driving easier with low level automation when car support the driving in his/her driving.

The term *workload* refers to the interaction between the task demands and the driver's capabilities in a certain driving situation.

Situation awareness incorporates the driver's understanding of the driving situation as a whole, including e.g. the traffic and (road) weather conditions, and of AV behaviour at any given time of the trip. It refers to perception of the elements in the situation, how their meaning is comprehended and how the status in the near future is anticipated. The focus (relevance) of situation awareness depends on the level of automation: With full automation, it is not necessary for the user to be aware of the driving situation (but they may still like to have the information), whereas in partial automation it is very important. For conditional automation the fast recovery of situation awareness is a challenge when the take back of control is required. Situation awareness is closely related also to the HMI through which the AV and its user communicate (what part of the information available to the vehicle is shown to the user).

Stamina (fatigue) means the energy level or vitality of the driver/user. In long monotonous driving or non-driving situations, e.g. on a motorway with little traffic, drivers may become tired, which has implications on their driving capabilities, to fully utilize the driving skills.

The term '*Frequency of take back of control'* relates to situations in conditional automation where drivers are requested to take back control at the end of ODD (system initiated), or they can themselves take back full control of the driving task when preferring to drive by themselves (driver initiated). From the user perspective, it is relevant how often and in which situations the driver needs to take over control and how early they get the indication of the requested take over. As this take over control situation is potentially risky, its frequency is of interest. Late take over requests may lead to poor situation awareness of the

driver when beginning to drive again. The frequency also affects the possibilities for secondary activities during the drive.

Driving experience concerns the experience (mileage) of the user of the AV that s/he drives manually by conditions and by road types. If the AV drives automatically e.g. always when on motorways, the human driver does not get experience of driving on motorway, etc. In the long run, the lack of driving experience affects the driving skills and capabilities.

c Quality of travel

Quality of travel concerns the characteristics of the AV use from the users' point of view. It includes the following topics: comfort and stress, use of in-vehicle time, traveling reliability and feeling of safety.

Comfort describes whether the ride feels comfortable or uncomfortable (e.g. due to harsh braking or fast longitudinal or lateral acceleration). It can also refer to the convenience of the services enabled by AD. S*tress* refers to the user's emotional stress (uncertainty, fatigue, distress, worry) related to the trip with an AV (e.g. stress due to uncertainty of AV behaviour or take-back-control situations; or decrease of stress due to removed need for searching a parking space or drive (manually) e.g. in congestion). *Use of in-vehicle time* refers to possible non-driving related secondary tasks in the vehicle like use of entertainment, which can be allowed if the driver is not constantly in charge of monitoring the environment. The actual in-vehicle activities depend also on the users' choices, preferences and on e.g. their proneness to motion sickness. The use of in-vehicle time is related to the value of time when traveling.

Traveling reliability in this context means primarily how well the trip duration can be predicted (travel time reliability), but it may also concern other aspects of the trip such as the costs of the journey, reliability of automated services, accessibility and reliability of travel chain. *Feeling of safety* refers to the subjective safety when traveling, i.e. whether the driver feels or experiences that the automated vehicle is driving safely and also ensures the safety of other road users.

d Transport offering

Transport offering refers to the potential changes in mobility options available to users.

Completely new mobility services can develop due to the introduction of AV (*New possibilities for mobility services).* If useful new services arise to meet people's mobility needs (such as car sharing service, robotaxis, automated shuttles), this may lead to changes in car ownership.

Vehicle availability means certainty that there is a vehicle available for a user when (s)he needs it. This is linked to the mode choice, car ownership and traveling reliability.

e Driving quality

Driving quality relates largely to the changes in driving behaviour on a vehicle level (*Vehicle operations)* and how well it is able to drive but also on traffic flow level and how smooth it is. Driving quality concerns the translation of impacts on single vehicle operations to the road network in a wider scope. Changes in individual behaviour of vehicles, such as choice of headway and speed, have consequences on the speed patterns of a group of vehicles traveling in the same direction, reflected e.g. as shockwaves within the traffic flow. These sudden behaviour changes of single vehicles and the impact on them on traffic flow level depend on the capabilities of the AV, and the extent of impacts in specific situations depends, among others, on the penetration rate of AVs, their situation awareness and capabilities of car following, as well as on the traffic volume on the road.

Synchronisation of speed patterns may occur with higher penetration rates of AV (or CACC), or in situations where overtaking is not possible and a platoon/queue of vehicles drives with close to equal speed. In manually driven vehicles, keeping a constant speed is not easy, and the speed of individual vehicles typically oscillates around a certain speed. The amount of oscillation depends for example on the state of the driver, possible distracting factors and the surrounding traffic situation. AVs are better capable of keeping a certain set speed. This is especially true for connected vehicles, which can better anticipate upcoming traffic situations. Synchronised speed patterns lead to a smoother traffic flow with less disturbance, especially relevant for situations with high traffic volume and/or bottlenecks (e.g. accidents, lane closures).

Variance in alignment of driving refers to the lateral alignment of a group of vehicles traveling in the same direction. Lateral position in the lane can affect the abrasion of the pavement and e.g. rut formation, if a platoon of vehicles drives exactly on the same track in a lane.

Driving errors refer to mistakes in driving behaviour by individual vehicles/drivers. On the one hand, automation can reduce driving errors (e.g. by preventing unintended lane departures, obeying the speed limits or by not being distracted when driving), but on the other hand new driving errors can occur. For example, an early stage AV may not park exactly between the markings of a parking place or not be able to detect an incident on the road early enough, or an AV may misinterpret the road markings or suffer from errors in map information.

Transitions from AD to driver refers to the situations when the driver is required or chooses to take back control of the driving task. This may have implications for the traffic flow, e.g. the vehicle may lower its speed temporarily until the driver is in the loop. *Frequency of harsh braking* can increase or decrease with AV compared to manual driving, largely depending on AV capabilities to perceive certain events such as stopped vehicles downstream early enough. This is closely related to *Frequency of shockwaves*, which may change depending on AV capabilities and on the traffic situation. *Limited/extended visibility* of AVs compared to manual vehicles refers to the sensor systems implemented in the AV and the visibility (detection of objects and the interpretation of the situation) they provide to the vehicle or driver when compared to the human capabilities in detecting the situation without technical support. This includes for example how well the immediate surroundings of the car are perceived, at which distances and in

which angles the sensors work, and how reliably they provide information in different conditions (weather conditions, in case of an obstacle etc.). *False/better anticipation of intentions* is related to interpretation of information received by any sensors, AV vs. human. AVs (technology) may not be equally good as a human actor (the driver) in perceiving and interpreting all weak signals, or at the least AVs may not be capable of covering the huge variety of situations in road traffic. Specifically, this can be seen in anticipating the intentions of other road users, pedestrians and cyclists in particular. On the other hand, AVs do not get fatigued or focus on other activities than driving.

f Behaviour and skills

The topic 'behaviour and skills' is largely related to the personal mobility behaviour of individual users (and non-users) and the skills required for that. With the introduction of AVs, the daily mobility choices of the AV users may change in terms of *Number of journeys* made, choice of *Destinations*, *Transport mode selection*, *Timing of journeys* and *Route selection*.

For example, automated valet parking may lead to driving more by car into the city centre instead of using public transport, as finding a parking space is often difficult in city centres (and some people do not like to park in narrow parking garages etc.), highlighted in busy hours. If car travel is more convenient, more people may choose to use a car instead of public transport or active modes. In partial automation, route choices may change e.g. to favour longer routes to travel on motorways and take use of a motorway pilot function.

Harm by delays describes the perceived harm by travellers resulting from delays in traffic, addressing both emotional and practical aspects. This may change with AD, for example some delays may be considered less harmful if the time spent in the car can be used in productive ways, reflected in the value of time.

Behavioural adaptation of non-AVs may occur if the drivers of manually driven vehicles start to copy driving behaviour of AVs, for example by using smaller or larger headways or by strictly obeying the speed limits. Behavioural adaptation may also apply to VRUs who start trusting that all vehicles will stop for them, if AVs are likely to do so, and may change their behaviour e.g. when crossing roads.

Driving skills may be affected when ADF are mature enough to take over a large part of the driving. Driving skills refer not only to manoeuvring the vehicle at the operational level but also to higher-level skills such as focusing attention to the relevant, anticipating driving situations, interacting efficiently and safety with the other road users etc. It is expected that ADFs will at least in the short-term work only in good conditions. Therefore, drivers need to drive themselves in bad conditions, which have a higher accident risk, especially when accompanied with less driving experience overall. (This may lead also to personal mobility impacts, e.g. less travel or less car travel during adverse conditions.)

3 Impacts on transport system (*Block 3*)

a Safety

Safety of road transport is defined indirectly in terms of *Number of crashes* and *Severity of crashes* for travelling (exposure) in road transport. A source of data are the public statistics in which severity can be found in four categories: fatal crashes, severe injury crashes, injury crashes, and property damages only (not, however, in all statistics). In addition, simulations and conflict techniques can be used to assess changes to traffic safety with AV.

b Efficiency

Network *efficiency* refers to lane, link and intersection capacity and throughput in a regional transport network. Efficiency also refers to travel time (as part of the 'Personal mobility': Duration of journeys) and travel time reliability [10].

Road c*apacity* can be measured as the maximum throughput which is the number of vehicles per hour through a particular road section or intersection approach, normalized to number of lanes and proportion of green time (where relevant) [10].

Peak period travel time along a route is discussed separately because during these hours, even a small reduction of capacity would have severe impacts in the areas where peak hour traffic exceeds the capacity already in the current situation.

c Infrastructure

Automated vehicles can be connected to the *Infrastructure (V2I)* and thereby receive information collected by infrastructure based systems, and be able to utilize it. *Quality of road surface*, including road markings and road maintenance, is critical for automated vehicles as localisation can be based at least partly on road markings, and the AVs may have difficulties to detect damages on the road surface such as potholes. If all AVs position themselves strictly to the position of the lane, the quality of the road surface may suffer sooner than for manual driven fleet. *Use of hard shoulders* becomes important in high level of automation when hard shoulders may be needed as safety harbours in case of malfunctioning of the AV (as part of the minimal risk manoeuvring). If hard shoulders are dedicated to being the safety harbour for the stopped AVs, then they cannot be used as temporary lane.

d Environment

Impacts on the Environment include both tailpipe Emissions and greenhouse gases (CO_2, NOX, CO, PM10, PM2.5, VOC emissions in total per year and per vehicle-km or mile) and the Energy use or consumption of the vehicle. The direct energy/emissions impacts come from the change in the driving cycle. Energy consumption can be analysed by vehicle km travelled (vehicle fleet) or by person km travelled. Changes in vehicle propulsion (e.g., electric vehicles) may also have a significant effect on tailpipe emissions. Noise can be measured as the annual average of the proportion of time when the noise level is above a certain threshold [10]. In addition to the amount of emissions, also the environment where they are produced is of importance.

Material use refers to all other material than moving power such as components needed to build AVs.

e Travel behaviour / Mobility / Personal mobility

A traveller may respond to new transport options, such as AV, by changing their *travel behaviour*. The *Share of transport modes* may change in road transport or in the whole transport system (affecting multimodality). There may be more or fewer trips affecting the *Total number of journeys* (per week, in total and per inhabitant) or changes in the *Duration* (in total and per inhabitant) and in *Length of journeys* (the total kilometres or miles travelled per week in a region).

f Land use

The *Need for parking slots* refers to different types of spaces needed for parking, such as the need for underground parking (m^2) and the space needed for street parking in city centre areas (m^2). For example, the use of private cars, car sharing, features and AV functionalities and urban policy affect the amount of space needed [70].

Automated driving may increase the share of car trips out of all travelling. Due to its convenience and lower value of time, it may lead to an increase in urban sprawl and thereby affect the *Density of housing*. Planning and construction policy and offering of public transport services are means to influence density of housing.

Location of employment refers to distance of employment in relation to the city centre and major housing areas (km on average). Use of AD in commuting and willingness of employees to commute longer trips have influence on land use. Also the requirements that AVs have for parking can influence the location of the employment.

4 Impacts on societal quality of life (*Block 4*)

a Public health

Morbidity refers to diseases or disabilities and takes into account the duration of the disease; it can be weighted by severity. Mortality is a measure for years of life lost and potential years of life lost. Road traffic can affect mortality and morbidity indirectly for example by increasing pollution and particles in the air and by influencing physical activity of citizens (the share of active transport modes), or directly through road crashes causing injuries and deaths.

b Individual Quality of life

Individual Quality of life (QoL) refers to both the quantity and quality of life lived. It is accomplished as the outcome of *Social, Physical, Mental* and *Economic wellbeing.* QoL assumes that health is a function of length of life and quality of life; overall life expectancy by the amount of time lived in less than perfect health. Physical and mental wellbeing are directly linked to health; social and economic wellbeing are

more indirectly linked to health but are also as such important indicators of QoL.

c Equity

Equity means that all citizens have equal access to road transport services independent of road user type, *social* or *economic* background, car ownership or *region* they live in. In an optimal situation accessibility can be provided for all potential road users on a reasonable level between any desired locations.