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Confidentiality	

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Summary

The effect of the interaction between Cooperative, Connected and Automated Mobility (CCAM) in scenarios where the ratio of conventional and intelligent vehicles is a topic of interest for researchers and the industry. There is an expected effect on road safety and traffic efficiency stemming from the coexistence between Connected Automated Vehicles (CAVs) and other non-connected, non-automated road users like disconnected pedestrians or legacy vehicles – which we group under the term Multi-modal Road Users (MRUs). These effects, either positive or negative, might not grow linearly with increased adoption rates and, furthermore, it is realistic to expect MRUs to share the road with CAVs even as outliers in the fleet. Thus, identifying and analyzing if existing and developing safety metrics apply to a near full-CCAM environment is crucial, specifically, if human factors (which affect conventional driving) continue to influence safety and efficiency when full connection and automation is expected.

This pre-study explores the literature and performs a simulation-based analysis of these risks and human factors on road safety and traffic efficiency. Starting from an exploration of the literature, where groundwork exists on existing and expected risks and mitigations, we map these risks to scenarios where full CAV driving is expected. We identify that some of the humanly influenced risk factors that affect the Dynamic Driving task (DDT) are mitigated, while some other (e.g., decision making at the design stage of CAVs) might even create more heterogeneity. Then, in the simulation stage, we identify that heterogeneity is what influences safety and efficiency, and that it is not only the ratio between CAVs and MRUs that affects convergence but also the place in which heterogeneous vehicles are placed in the flow.

Human Factors, Risks and Optimal Performance in Cooperative, Connected and Automated Mobility

1. Background

Vision Zero is a Swedish-born global initiative aimed towards having zero deaths and zero in traffic accidents by 2050 [1]. Actions towards Vision Zero are underway in several scopes and domains: law enforcement, education, vehicle design, adaptations to road infrastructure, and information technology in different ways and forms. For the latter side, the use of Intelligent Transport Systems (ITS) is one of the cornerstones of Vision Zero, e.g., using Cooperative, Connected and Automated Mobility (CCAM).

For CCAM, the road to Vision Zero has been divided in incremental steps called Days, ranging from 1 to 4. For each element of CCAM (i.e., cooperation, connection, and automation), different functionalities are expected to appear on each day, e.g., higher levels of automation [2] in more operational design domains (ODDs), more modes of communication, and the ability to cooperate explicitly (i.e., coordinate).

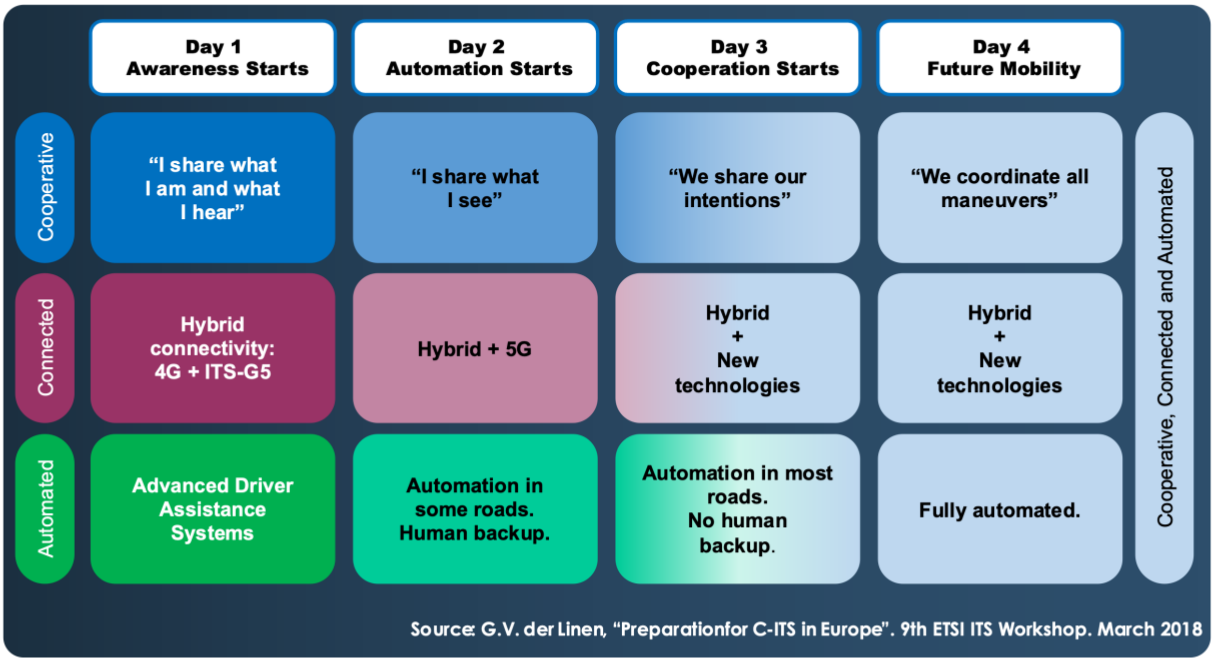

Figure 1. Vision Zero Days

Figure 1 shows a summary of what is expected on each day. However, even though full-CCAM support is expected in the *fleet* (i.e., all vehicles on the road), market trends and consumer behavior [3] can hint that Connected Automated Vehicles (CAVs) will have to coexist with Multimodal Road Users (MRUs) – non-CAVs, vulnerable road users, and CAVs from earlier generations.

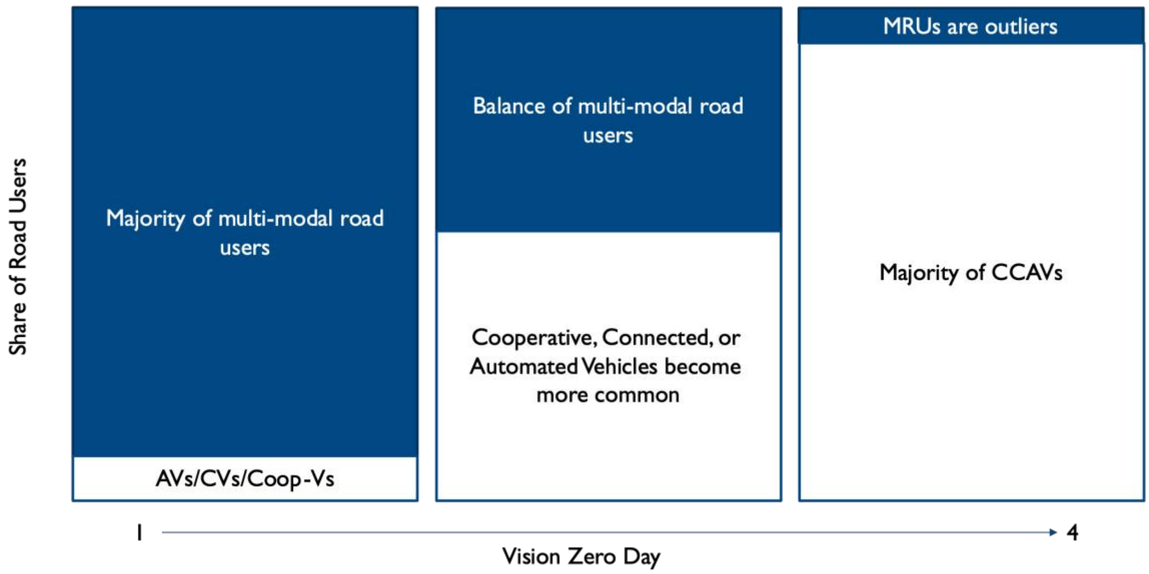

Figure 2. Share of CAVs and MRUs on the road to Vision Zero

A representation of our assumption is presented on Figure 2, where we show MRUs as outliers. This prompts us to our main question, which is whether we can measure the effect of this coexistence in risk metrics, and whether currently existing or proposed risk metrics can help us visualize incoming risk scenarios.

The main challenges for this pre-study are:

1. The fact that services for different days are being developed in parallel, e.g., the protection Vulnerable Road User (VRU) and Collective Perception protocols – Days 1 and 2 respectively – in the European Telecommunication Standards Institute (ETSI) ITS stack are being developed concurrently. Furthermore, since the VRU awareness basic service was not part of Release 1 of ETSI ITS, it is considered as Day 1.5 in the Study on the Deployment of C-ITS in Europe: Final Report [4]. This blurs the lines that *separate* days and mapping services to days becomes challenging.
2. Simulating CAV-VRU interactions is a nontrivial exercise. Validated simulation tools provide support for Connected *or* Automated mobility. However, coming up with a toolkit to assess both at the same time brings even more questions such as whether intelligent vehicles will react the same way to given inputs or if they will follow diverging strategies. The way we approach this challenge and the preliminary insights that we gained are explained in Sections 3 and 4.

2. Project set up

2.1 Purpose

The purpose for the project is to further progress in CCAM technologies deploying and thus addressing Vision Zero mission. While it is expected that CAVs become pervasive, MRUs, such as pedestrians, bicycles, non-connected legacy cars might obstruct the convergence towards an optimal performance.

2.2 Objectives

In discussions on smooth transition towards CCAM the following questions arise:

1. How can road risks be assessed in Day 4 scenarios where CAVs are dominating but still coexisting with non-connected, non-cooperative MRUs? (see Fig. 2)
    - Are existing risk models valid for future mobility?
    - What are the parameters that affect the accuracy of risk assessment methods?
2. What are the optimal requirements for information, network performance and data processing to respond efficiently to the presence of MRUs?
    - How do different types and levels of communication affect performance safety and efficiency?
    - What are the optimal requirements (e.g., data, technology, infrastructure) to respond efficiently to MRU factors in hybrid scenarios.

In this pre-study, we have two main goals that systematize the search for answers to these questions:
Goal 1 (risk metrics): to identify scenarios requiring enhanced risk metrics. It includes:
- providing risk map for hybrid road scenarios (CAV+MRU)
- identifying parameters that divide scenarios into groups
- matching risk assessment methods/models available

Goal 2 (CAV performance): to define optimal response requirements. It includes:
- investigation of the effect of different levels of CCAM (e.g., local awareness, collective perception, statistics, intention sharing) on road safety and traffic efficiency for the Day 4 scenarios
- proposing optimal network and data requirements based on the previous point.

2.3 Project period

2023-09-01 – 2024-09-31 (originally 2023-09-01 – 2024-08-01, extended for 2 months)

2.4 Partners

Organization	Person	Role
Halmstad University (coordinator)	Elena Haller	Project Manager
	Oscar Amador Molina	Project Member
VTI	Maytheewat Aramrattana	Project Member
RISE	Lei Chen	Project Member

3 Method and activities

There are two main activities that map to our goals. Goal 1 is approached through a systematic review of the existing literature on risks stemming from the adoption of CAVs as well as updates on expected services for the second half of Vision Zero. For Goal 2, a simulation-based pre-study is performed to measure the effect of a mixed fleet.

3.1 Literature Study

To identify metrics and models that are used to estimate road risks as well as Day 3+ road scenarios the literature study has been performed. After a systematic literature exploration, we chose to focus on deliverables of 2 projects and 1 consortium together with one survey paper.

1) SafetyCUBE (Safety CaUsation, Benefits and Efficiency) 2015-2018 - a research project funded by the European Commission under the Horizons 2020, the EU Framework Program for Research and Innovation, in the domain of Road Safety [15]. The primary objective of the SafetyCUBE project was to develop a road safety Decision Support System (DSS) to reduce casualties of all road user types and all severities in Europe and worldwide. Day 0 risk factors, i.e. ones that are currently present on the road and are not related to CAVs, are grouped into a 3-tier topology that becomes a starting point for our research.
2) Levitate (Societal Level Impacts of Connected and Automated Vehicles), 2019-2022 – a research project funded by the European Commission under the Horizons 2020, the EU Framework Program for Research and Innovation, in the domain of Road Safety [18]. It was aimed to prepare a new impact assessment framework to enable policymakers to manage the introduction of connected and automated transport systems, maximize the benefits and utilize the technologies to achieve societal objectives. One of outcomes for this project is a study of Day 1+ risk factors related to automated and connected services. That research allows us to compare Day0 and Day 1+ risks and follow their evolution.
3) Car-2-Car consortium – provides a set of applications at Days 1 to 3 and beyond (Day 3+) in a roadmap 0. The Car-2-Car consortium categorizes C-ITS applications and deployments into Day 1 (Awareness Driving), Day 2 (Sensing Driving), and Day 3+ (Cooperative Driving). With respect to the roadmap released by the consortium, we focus on Day 3+ scenarios, namely cooperative driving. This means that CAVs in these scenarios are not only aware of each other's intention and position, but also coordinate their maneuvers accordingly to improve safety and efficiency. The description and functional requirements for these applications and the services that support them come from stakeholders, which give us a realistic outlook of what is expected on Day 3+.
4) In the context of Day 3+, CAVs play an important role in future. Therefore, another important literature is the framework outlined in [6], where the authors proposed a Measure of Effectiveness (MOEs) framework along with indicators when considering CAV applications based on their benefits with respect to safety, mobility, and environmental. They also suggest that one application may have one or more benefits. Furthermore, the authors categorized CAV applications into three categories: i) vehicle-centric: the CAV application that is driven primarily by on-board units on the vehicles involved and have strong focus on controlling the ego or surrounding vehicles (e.g., cooperative adaptive cruise control); ii) infrastructure-centric: the CAV applications that are analyzed and processed at a centralized road infrastructure (e.g., variable speed limit, GLOSA); and iii) traveler-centric: this type of CAV applications put emphasis on sending and receiving information from other travelers (e.g., pedestrian collision warning).

3.2 Simulations

We perform two sets of simulations to assess (1) the effect of heterogeneity in the traffic flow when conventional and CCAM-enabled vehicles coexist, and (2) network performance when different generations of a protocol share the medium. In order to ease the understanding of the different variables in play, we simulate (1) only in a traffic simulator (i.e., SUMO [7]), and (2) in a vehicular networking simulator (i.e., Artery [8]).

There are multiple built-in car-following models in SUMO. By adjusting model parameters one can use them to represent the behavior of a human driver or automated vehicle. The problems that arise are

(i) Is it better/makes more sense/etc to use the same model (with different parameter settings) -for both legacy vehicles and CAVs?
   a. If yes, how parameters should be adjusted? – parameters differ between models, i.e. in Krauss, we have desired speeds, deceleration capabilities, minimum inter-vehicle gaps and *driver imperfection*; whereas in other models, additional parameters are used, e.g., to represent cruise control mechanisms.
   b. If not, is a setup with two different models representative? (i.e. if two models are compatible with each other) - The literature [9] already identifies this problem of *compliance*, where both CAVs and MRUs can potentially push rules to the limit or even go above permitted limits. This is supported by studies on driver behavior and driving styles [10]. Thus, it is crucial for us to explore these factors, which will probably affect convergence even in a fully automated fleet, since *driving styles* are likely different between brands.

(ii) Is there a model where safety, efficiency and speed are maximized together? – SUMO has implementations for models like Krauss and other models validated in the literature (e.g., adaptations to Krauss considering road slopes; the Intelligent Driver Model – IDM, which has more conservative lane-gap assistances)

For addressing (2), we use Artery and get results directly. However, one should notice that there is no direct way to join results from network simulator and SUMO, i.e., making vehicles at SUMO react to messages from Artery. SUMO operates with ideal-nonideal driving models and doesn't separate imperfections by their nature (network, sensing, etc.). So, the connectivity is derived from empirical data coming from CAVs, and the network effects are not "visible" directly but included into kinematic parameter(s).

3.2.1 Simulation Scenario CAVs vs MRUs (1)

For (1), the mix between connected and conventional drivers is tested in a suburban scenario (Flygaregatan roundabout, Halmstad): a two-lane priority road that connects the center of a city to neighborhoods in the outskirts and traverses an area with schools, stores, and sports facilities. There is a roundabout with a pedestrian crossing where VRUs are injected randomly.

Figure 3 shows the map we use to simulate the interaction between CAVs and MRUs. In this case, we assess the performance of the traffic flow when pedestrians cross the vehicle roads (black lanes) near the roundabout. The fleet consists of automated and conventional drivers.

Figure 3. SUMO map and real-life counterpart of the simulated scenario: CAVs vs MRUs

To simulate automated drivers, we start from two main assumptions that affect the choice for car-following models. SUMO, by default, uses Krauss to model the behavior of vehicles. They have a set of parameters: maximum speed, minimum gap between vehicles, deceleration settings, that are followed with different levels of strictness. There is another parameter, *driver imperfection*, that goes from 0 to 1 and is by default set at 0.5. This determines how a vehicle sticks to the other kinematic parameters. We assume, then, that an automated vehicle would behave as a perfect driver, thus, we set the driver imperfection value to 0.

However, SUMO also has implemented a car-following model that is based on traces of vehicles with cooperative cruise control capabilities [11]. This model, originally stemming from Krauss, adds collision avoidance and gap control modes that affect the behavior of a vehicle when others are close.

This brings us to a crossroads where we have to start from two competing assumptions:

a) automated vehicles will maximize efficiency and behave as the *perfect driver* trying to stick to the maximum allowed speed and minimizing the gap between vehicles, or
b) automated vehicles will maximize safety and try to decelerate preemptively when approaching other neighbors although *compromising efficiency* by not going as fast as possible for as long as possible.

Thus, an encompassing assumption is that, even with a fully CCAM-enabled fleet, the way automation is implemented by different manufacturers will bring an extra layer of heterogeneity. However, for this pre-study, we just compare – separately – the coexistence between conventional drivers (modelled by half-perfect drivers in Krauss), against two models for automation: one with perfect drivers in Krauss, and one using the CACC car-following model.

Parameter	**Value**
Number of vehicles	200
Vehicle flow	Poisson, average 0.2
Number of pedestrians	29
Pedestrian flow	0.01/s
Runs (time)	100 (3000s)
Model for CAVs	Krauss (perfect driver), CACC
Model for conventional driver	Krauss (0.5 imperfection)

CAV penetration rate	0, 25, 50, 75, 100%

Table 1. Simulation Parameters (CAVs vs MRUs)

Table 1 presents the rest of the simulation parameters. The metrics we obtain can be divided are:

- Safety
  - Collisions and emergency breaking events
- Efficiency
  - Average speed, time loss

We perform one hundred runs and obtain average values that are shown in the results section.

3.2.2. Different generations of connected technologies (2)

For (2), we simulate in a 5km-long segment in a highway with four lanes on each direction. A source vehicle sends a message intended for a rectangular Destination Area covering 4000x100m behind the source. We send messages to a connected fleet with a density of 30 vehicles/km per lane with different releases of the ETSI GeoNetworking protocol (i.e., Release 1 and Release 2).

Figure 4. Scenario for GeoNetworking coexistence evaluation

Figure 4 shows a representation of our scenario. We simulate the dissemination of an emergency message at 1Hz from a source node (blue car) to a geographical area of 4000m x 100m (Destination Area, delimited by the red line) behind the source node. This allows evaluating the dissemination, e.g., of a message advertising of a risk such a stationary vehicle or slippery road conditions. Vehicles execute either Release 1 or Release 2 of the ETSI GeoNetworking standard for multi-hop communications, but we assume messages are mutually intelligible.

Parameter	**Value**
Access Layer protocol	ITS-G5 (IEEE 802.11p)
Channel bandwidth	10MHz at 5.9GHz
Data rate	6 Mbits/s
Decentralized Congestion Control	ETSI Adaptive DCC
Transmit power	20mW
Path loss model	Two-ray Interference model
Maximum transmission range	1500m
CAM packet size	285 bytes
CAM generation frequency	1—10 Hz
CAM Traffic Class	TC2
DENM packet size	301 bytes
DENM Traffic Class	TC0 (Source) and TC3 (Forwarders)
DENM lifetime	10s
Duplicate Packet List size	10

Release 2 penetration rate	0, 25, 50, 75, 100%

Table 2. Simulation parameters: different releases of connected technologies

Table 2 presents the simulation parameters for this evaluation. The performance metrics are oriented towards network performance:

- Packet delivery ratio (PDR): the number of successful individual receptions of a message in the Destination Area divided by the number of vehicles in the area at the time of DENM generation.
- Number of transmissions: the total transmissions including those from the source and those from the forwarders.

The simulator includes the complete ETSI ITS stack and vehicles send CAMs and the source and forwarders also send DENM traffic. We simulate measure for 30s after a warmup period of 120s.

4 Results and Deliverables

4.1 Literature Study Results

4.1.1 Overview

Speaking of risks, the assessment methods can be categorized (a) by assessment level and (b) availability of real-world data.

Levels of assessment. Three levels of investigation are defined based on approximation degree [12].

1) Macro-level refers to highest approximation level operating with averaged vehicle fleet and RUs characteristics. It can be expressed in terms of mortality index, severity rate, hazard ratio etc.
2) Meso-level is also aggregated data based with more infrastructure information included (e.g. geometry, weather). This level is indicated for smaller surveys and allows for accident map construction.
3) Micro-level analysis relies on single accidents (disaggregated data) joint with previous layers. It allows for defining causes of particular events.

For all the levels there are three factors that affect number of accidents and their severity: characteristics of the road environment, traffic conditions and road user behaviour.

Data-based methods. In cases where there is enough data, post-factum assessment techniques are applicable. Both quantitative and qualitative metrices can be obtained.

1) Quantitative approaches. Multicriteria analysis with several safety vital parameters are in use on all levels. E.g. at meso-level [13] by means of Simple Additive Weightage (SAW), analytical hierarchy process (AHP) and Fuzzy AHP such indices as road geometric characteristics, pavement condition, traffic signs and marking were ranked by severity levels 1-5 with severity scores (SCs) adopted from FHWA guidelines. As for macro-level, by method of conflict situations [14], risk numbers can be obtained by combining accident and safety coefficients.
2) Qualitative approaches. Data-based (road statistics and interviews) research done in project SafetyCUBE [15] presents qualitative assessment of risk factors affecting road safety. Risks are sorted according to 3 level topology and

categorized by severity level (red, yellow, green). As a result, a new DSS is proposed.

Other methods. In cases when real-world data is not available, simulations and pre-factum approaches can be used.

1) Pre-factum approaches. When accident data is not present in database, one has to rely on other techniques, e.g. automated video image analysis [Italy]. In this study Risk number (R) is defined as a product R=D*V*E of Danger (D), Vulnerability (V) and Exposure (E) (Crash Modification Factors, CMFs [16]). The computations are performed for 3 RU categories: pedestrians, cyclists and motor-Vs. For each category all CMFs (D, V and E) are associated with road attributes that were detected/recognized from video images.
2) Simulations. Scenarios with high penetration rates for CAVs can only be simulated (driving simulator experiments, traffic simulation). Though generalizability to other situations is uncertain, such numerical experiments give a starting point for research on Future Mobility [17].

4.1.2 SafetyCUBE

We have adapted the extensive risk topology from SafetyCUBE to identify which Vision Zero Days would apply to and whether it would affect an ecosystem with only CAVs (i.e., Day 4, if we consider MRUs to be inexistent). Table 3 shows our adaptation. The only note (denoted by *) is that while SafetyCUBE includes age as a factor that affects, e.g., functional impairment and risk taking in human drivers, we also take it as a factor for CAVs, since vehicle age might influence characteristics such as cooperation, communication, and perception abilities (which, in the end, is analogous to what SafetyCUBE does for human drivers).

Table 3. SafetyCUBE Risk Topology Adapted to Days and CAVs

	Risk Factor	**Affected Days**	**CAVs**	**MRUs**
Road Users	Speed Choice	1—4	X	X
	Influenced Driving - Alcohol	1—3		X
	Influenced Driving - drugs	1—3		X
	Risk Taking	1—4	X	X
	Fatigue	1—3		X
	Distraction and inattention	1—3		X
	Functional impairment	1—4	X	X
	Insufficient knowledge	1—4	X	X
	Emotion and stress	1—3		X
	Misjudgment and observation errors	1—4	X	X
	Traffic Rule Violations	1—4	X	X
	Personal factors	1—3		X
	Age*	1—4	X	X
	Disease and disorders	1—3		X
Infrastructure	Exposure	1—4	X	X
	Road Type	1—4	X	X
	Road Surface	1—4	X	X

	Road Environment	1—4	X	X
	Work zones	1—4	X	X
	Alignment deficiencies – road segments	1—4	X	X
	Cross-section deficiencies – road segments	1—4	X	X
	Traffic control – road segments	1—4	X	X
	Alignment – Junctions	1—4	X	X
	Traffic control – Junctions	1—4	X	X
Vehicles	Crashworthiness	1—4	X	X
	Injury mechanism	1—4	X	X
	Protective equipment design	1—4	X	X
	Relevant factors in crash data	1—4	X	X
	Technical defects / Maintenance	1—4	X	X
	Vehicle design	1—4	X	X
	Visibility / Conspicuity	1—4	X	X

We use a pruned version of this table (one where Days below 4 and factors not affecting CAVs are taken out) and map it with risks and mitigations described on Section 4.1.3 and Day 3+ services described in Section 4.1.4 to create a *map* that is shown and explained in Section 4.1.5.

4.1.3 Levitate

The Levitate project investigates impact of increasing rate of CAVs in the fleet. Authors categorize impacts as *primary* (direct) consequences of driving tasks being performed by vehicles; and *secondary* (indirect) changes in other factors that in their turn affect road safety [17].

Among primary impacts, there are risks that mitigate when CAVs are pervasive. Firs, *reaction times*, since CAVs have reduced of reaction times and driver variability, compared to human drivers, and that results in increased road safety for all penetration rates ([19], [20], [21], [22]). Also, *traffic violations* and *driver degraded performance* become eliminated with CAVs on the road [23].

However, some **new risks** arise. Among them [17]:

- *Degraded performance*. In unfamiliar situations that are not in CAV's database, Issues in its control system or programming failures could result in an accident.
- *Cyber-attacks*. As more elements in vehicles rely on digital data processing, cyber security role grows. According to the work in [22], it is impossible to prevent all cyber risks even though attacks would require high capacities.
- *Transition of control*. Take-over times are affected by such factors as availability, engagement, automation level and prior experience [24]. Reaction times in take-over situations increase with level of automation [25].

4.1.4 Classification of Day 3+ applications

Based on the methodology in 0, Day 3+ applications defined in 0 are categorized. Since the applications in 0 were categorized with emphasis on communication patterns, some of them are grouped together in Table 4.

Table 4 Categorization of Day 3+ applications listed in 0 based on the framework proposed in 0

ID	Name	Short description	Goal[†]	Type[‡]
1	Platooning	Platooning application enhances adaptive cruise control (ACC) performance with V2X communication and includes support for lateral vehicle control depending on level of automation. This also includes cooperative maneuvers related to platooning such as forming, splitting, leaving, and merging platoons.	S/M	V
2	Target Driving Area reservation	A vehicle that is going to perform a maneuver informs other road users about the intention to occupy a road section.	S/M	T
3	Automated Green Light Optimum Speed Advisory	Extends the GLOSA by implementing automated functions for adaptation to the speed suggested by the infrastructure or computed by the vehicle	M/E	V/I
4	Optimized Traffic light information with V2I	Optimization of traffic light controller based on information received from CAVs by, e.g., updating its queue models and calculate more efficient traffic light phases.	M/E	I
5	Transition of Control Notification	A CAV that is about to give the control back to the driver can inform other traffic participants about this possibly risky event, or about the occurrence of a minimum risk maneuver in case the driver is not reacting accordingly	S	T
6	Improved Vulnerable Road User protection	A VRU is equipped with active C-ITS notification capabilities to alert other traffic road users or to let them automatically react to prevent risky situations	S	V/T
7	Cooperative maneuvering	CAVs initiate negotiation and cooperate to execute cooperative maneuvers such as merging, lane-changing, or overtaking.	S/M	V
8	Cooperative Transition of Control	CAVs can cooperate in organizing a transition of control, such that it minimizes the risks. The road infrastructure can participate in this cooperation by suggesting time or space where to safely trigger the transition of control.	S	V
9	Automated GLOSA with negotiation	(A group of) CAVs exchange information with the GLOSA advisor such that the feedback can be used by the traffic light controller to	M/E	I

		further refine the traffic light phase and time algorithms (e.g., to ensure a long enough and stable time to green for a big group of CAVs to pass the stop line before the next red starts)		

ǂ S = safety; M = mobility; E = environment
ǂ V = vehicle-centric; I = infrastructure-centric; T = traveler-centric

In the scope of Day 3+, some performance or risk indicators/factors specific to human drivers may no longer be relevant for CAVs and/or Day 3+ applications. To this end, we suggest that performance and risk indicators need to be revised according to their respective categories presented above for Day 3+ applications. Once the indicators are properly revised, existing methodologies can be applied to assess performance or risk of the C-ITS under a Day 3+ scenario(s).

4.1.5 Mapping existing and potential factors and risks for Day 3+

While we can safely assume that, on Day 4, CAVs and MRUs will still share the road in a mix where MRUs are outliers, centering on CAVs and the way existing risk factors still apply to the full-CCAM fleet helps at identifying not only mitigated risks but also new risks that come from, e.g., the intrinsic potential for a network to be attacked, the ability of a machine to identify and react correctly to objects and events, and the possibility of system failure.

Table 5. Map of risk factors for Day 3+ applications

	Risk Factor	Applications	Mitigated Risks	Potential New risks	Example
Road Users	Speed Choice	1, 2, 3, 7, 8, 9	Reaction times, traffic violations	Degraded performance, cyber-attacks	An adversary changes a speed limit sign (analog or digital). A vehicle's control system cannot keep velocity under the limit.
	Risk Taking	1, 2, 3, 5, 7, 8, 9	Traffic violations	Cyber-attacks	A CAV is programmed to act close to the limit or has "sport modes". An adversary sends messages with incorrect map information.
	Functional impairment	5, 7, 8	Reaction times, driver	Degraded performance	Intentional or unintentional

			degraded performance		errors in the OEDR subtask (e.g., due to sensor/system failure or an adversary sending "phantom" obstacles). Triggers to transition of control (intentional or unintentional)
	Insufficient knowledge	5, 8		Degraded performance, cyber-attacks	
	Misjudgment and observation errors	5, 8	Reaction times	Degraded performance	
	Traffic Rule Violations	1, 2, 3, 7, 9	Traffic violations	Degraded performance, cyber-attacks	An adversary sends incorrect information.
	Age (car age)	All		Degraded performance	Sensor or system failures. Incompatibility between CAV generations.
Infrastructure	Exposure	All	Traffic violations, driver degraded performance	Degraded performance, cyber-attacks.	Incompatibility between CAVs of different generations and between CAVs and the temporal or permanent characteristics of the infrastructure. Adversaries broadcasting "work zone" advisory messages to re-route traffic.
	Road Type				
	Road Surface				
	Road Environment				
	Workzones				
	Alignment deficiencies – road segments				
	Cross-section deficiencies – road segments				
	Traffic control – road segments				
	Alignment – Junctions				
	Traffic control – Junctions				
Vehicles	Crashworthiness	1, 7	Reaction times	Cyber-attacks	An adversary offers "phantom" maneuvers or platoons
	Injury mechanism	NA	NA	NA	NA

	Protective equipment design				
	Relevant factors in crash data				
	Technical defects / Maintenance	All		Degraded performance	Errors in the OEDR subtask. Inability to keep the expected speed.
	Vehicle design	All	Driver degraded performance	Degraded performance, cyber-attacks	New attack vectors or surfaces appear, and vehicles need quick firmware updates.
	Visibility / Conspicuity	2	Reaction times	Cyber-attacks	Spoofing a message sending an intention. Incompatibility with different releases of awareness services.

Table 5 shows the result of our literature exploration. It integrates the risk topology from Table 3 [15], with the expected risks and mitigations from [17], mapped to applications expected for Day 3+[5]. We have pruned the topology to only include full CCAM scenarios (i.e., Level 4+ automation and full connection), so human input is only required as assistance for OEDR subtasks.

The risk of cyber-attacks comes from the new attack vectors and surfaces that are open due to the nature of CCAM. Some of these risks are in the example column of Table 5, where some active attacks are described. For example, masquerade attacks where an adversarial node spoofs information that can cause the traffic flow to be re-routed, e.g., by announcing inexistent obstacles or roadworks. These attacks are present even from Day 1 services (like DEN), but new surfaces are open with maneuver coordination and intention sharing messages. An adversary can, e.g., steer a whole platoon into a dangerous location, or make it stop in the middle of a highway.

Furthermore, due to the nature of this topology, all these risk factors are also present for human drivers (i.e., MRUs). While some risks are mitigated, others are potentially exacerbated when CAVs and MRUs share the same road segment. Risk taking, as exposed in [15], is affected by the mix – if a human driver knows it is behind or in front of a CAV, it keeps different headways than if it drives next to another human. This is one of the factors we attempt at measuring in the simulation part of this project, where different driving strategies are tested.

Finally, extensive work must be performed to increase the granularity of this map. For example, adding urban, sub-urban, and highway scenarios and identify specific risks that factor in typical speeds, fleet mixes, and possible driving strategies and levels of compliance. This will in turn help decision makers and designers get a clearer picture of the risks that can be present when CCAM is present, as per Vision Zero, on all roads and at all times.

4.2 Simulation Results

In this section, we present the results of the experimental part of our pre-study. While the depth of this study barely scratches the surface of the problem of CAV/MRU heterogeneity, the findings are enough to determine that Human Factors will influence safety and efficiency not only within the Dynamic Driving Task (DDT), which includes operational and tactical decisions within a trip, but also in the strategy for trip completion. These two dimensions are discussed in these results, and another one – involving decision-makers – is presented in the Conclusion section.

4.2.1 Simulation Results: CAVs vs MRUs

Our results show that there is an expected correlation between the strategies for trip completion and safety and efficiency metrics. First, we present the results for efficiency metrics (average speed, time loss), since they help explain the effects that we observe in safety metrics (number of emergency events).

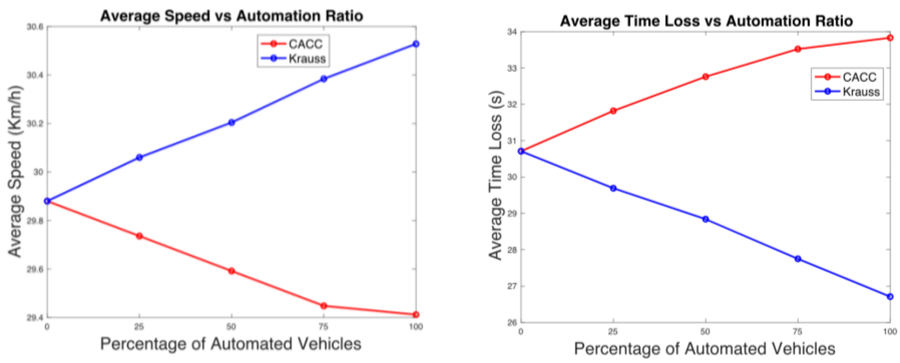

Figure 5. Traffic efficiency metrics for different CAV penetration rates

Figure 5 5 shows that, for the case where we consider CAVs *perfect* drivers using the same strategy as conventional drivers, efficiency grows linearly with increasing penetration rates. Speeds increase since vehicles drive as close to their desired speed as possible, and thus time loss (the time vehicles lose in a trip due to driving slower than their objective speed) decreases. However, when CAVs are use the CACC model and conventional drivers are Krauss 0.5-imperfect drivers, strategies differ, and convergence is affected. We can see it in the loss of linearity when we go from a mixed fleet to a fully CCAM-enabled fleet (even if there is a high proportion of CAVs). Furthermore, we see that the average speed is slower for the fully automated fleet using

CACC, which is in line with the expected behavior (e.g., keeping safer inter-vehicle distances, preemptive deceleration when approaching another vehicle).

These results fall in line with works in the literature [9, 26] and work related to this pre-study [27]. The probable cause for this non-linearity when strategies are mixed are explained by the fact that it is not only the proportion of CAVs/MRUs that matters, but also where they are placed in the flow – e.g., a single MRU between two CAVs driving without keeping a safe gap might affect the rest of the flow by not allowing it to converge into a safe speed. This adds another dimension to the problem of heterogeneity.

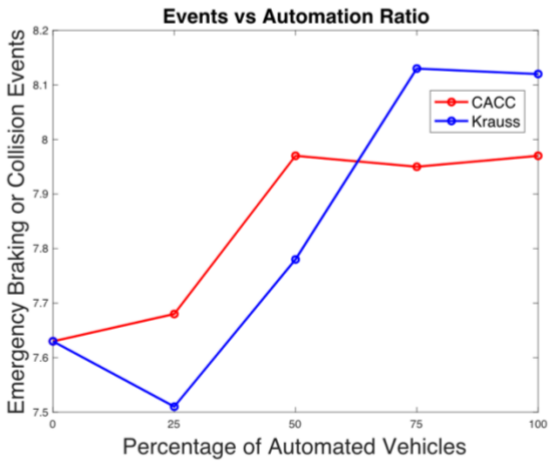

Figure 6. Road safety metrics for different CAV penetration rates

Figure 6 presents the effect of the mix in the number of emergency events (an aggregation of emergency braking and collisions). We see a slight increase in the number of these events in both scenarios, but only from 7.63 events in 3000 seconds to 7.95 in CACC and 8.1 for perfect Krauss. The region between the two heterogeneous combinations (i.e., 0% and 100%) shows also a zone of instability. However, further work is needed to fully grasp the effect of heterogeneity in these metrics.

4.2.2. Simulation Results: Different Generations of Connected Vehicles

The results of this experiment had the objective of proving the importance of keeping backwards compatibility between vehicles of different generations. Since the result of no compatibility would be trivial (i.e., vehicles of Release 1 only receiving to Release 1 messages, and vehicles of Release 2 reacting to both releases), we assess the performance of full compatibility between releases at the Network layer.

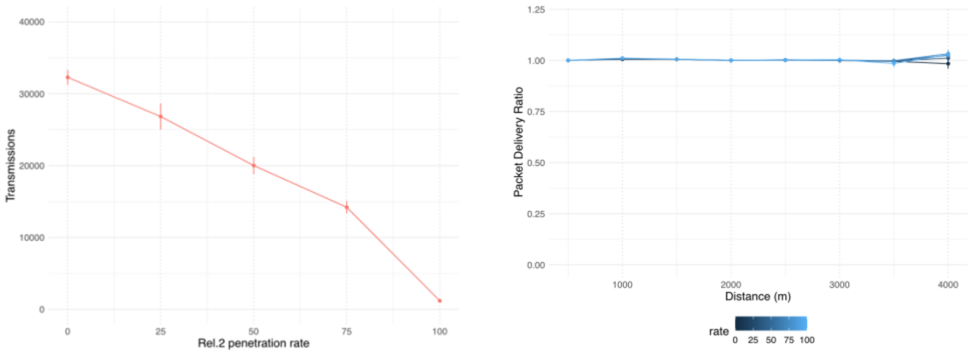

Figure 7. Network performance metrics for different releases of a VANET protocol

Figure 7 presents the results of full intelligibility but mixed efficiency. On the number of transmissions metric, there is an expected decrease in transmissions when more Release 2 vehicles are in the fleet. However, even a small proportion of Release 1 vehicles can create a broadcast storm since the redundancy mitigation techniques for Release 1 do not perform properly (hence, the updates for Release 2). However, the important metric is packet delivery ratio. The *undesired* redundancy in Release 1 causes messages to reach all nodes, yet the mitigation introduced in Release 2 does not affect reliability and increases efficiency an order of magnitude.

However, in network technologies, heterogeneity is multi-layered – something expected due to the layered nature of data communications. The vehicles in the simulation were all using one Access layer technology (ETSI ITS-G5). However, the current generation of vehicular networks also considers the possibility of using cellular communications. Also, even within ETSI ITS-G5, there are nodes that can operate in multiple channels (Multi-channel Operation – MCO), and different implementations can diverge in how they approach MCO: having one transceiver tune to different channels one at a time, or having multiple transceivers tuned to different channels (a. subset of all available channels). This heterogeneity applies to Layers 1 and 2 within a medium access technology. The next generation of vehicular networks will bring even more heterogeneity, even if they try to be backwards compatible by design – e.g., IEEE 802.11bd coexisting with 802.11p.

5 Conclusions, Lessons Learnt and Next Steps

5.1 Day 3+ risk assessment

1) Definition of Days. The first takeaway from 4.1 is that there is a completely blurred line between Day 3 and Day 4. Stakeholders, who are members of consortia that oversees implementations, now refer to services that enable or use cooperation as Day 3+ services. We attribute this to the way services have been developed, validated, and deployed in the past, with Day 1 and Day 2 services being part of the same *batch* or *release*. However, it is worth mentioning that there shall be a clear distinction between what is expected originally for Days 3 and 4. Full cooperation (i.e., Day 4) depends on agents knowing each other's goals and strategies and reaching an explicit consensus. Thus, even *area reservation* and *cooperative maneuvering* are labeled as Day 3+, *area reservation* is an example of Intention Sharing (Day 3), and *cooperative maneuvering* is an example of Maneuver Coordination (Day 4). In other words, Day 4 expects from vehicles to reach a state where they can exchange intentions and **reach**

a consensus. Vehicles that are not full-CCAM enabled will potentially stay on Day 3, since they might be able to share and read intentions but not to fully cooperate.

2) Lack of real-world data and limited simulation capabilities. The data available to assess risks comes mostly from simulations. It is understandable, since high densities and penetration rates for CAVs are not achievable in real scenarios. The problem with the currently available toolkits is that 1) there is still the need for a full-CCAM simulator (with services beyond Day1), and 2) that models for CAVs also depend on how CCAM is implemented by different makers. One of our next steps is to add full-CCAM characteristics to an already validated simulator.

This lack of data causes another issue that we have identified:

3) Qualitative risk assessment and research methods. Projects that are large in scope also use methods where potential risks and mitigations are foreseen by experts (e.g., using the Delphi method), who can converge into a set of risks, raise the alarm into risks not previously seen, but also miss some risk vectors or surfaces. Thus, there is a need for quantitative and systematic assessment of the foreseen risks with aims of finding not only mitigations, but also other currently hidden risks.

Finally, for this part of the project, our next step is to add more granularity and layers to our map. For example, adding urban, sub-urban, and highway scenarios, we can identify which risks get amplified. These layers would allow us to play with factors such as expected speeds and expected presence of MRUs and help us find risks and possible mitigations.

5.2 Mixed fleet

In line with recent works in the literature, we identify a zone of instability when there is heterogeneity between conventional and automated driving. The penetration rate of CAVs per se is not the only factor that affects safety and efficiency – the place that heterogeneous elements occupy in the flow plays a significant role. Thus, techniques that allow the integration of flows by vehicle types (e.g., platoons of homogeneous vehicles) is an option to ensure performance indicators. However, this requires a level of cooperation that some CAVs might not be capable of in early generations.

In terms of connectivity, the Next Generation of Vehicular Networks (e.g., 6G, 802.11bd) will bring even more heterogeneity. In this study, we analyzed the effect of having two generation of Network & Transport Layer protocols but with homogeneous characteristics at the Access Layer. Once 802.11bd becomes adopted, interoperability with 802.11p will be challenging although not impossible at the 5.9GHz band. However, 802.11bd has the capability to operate in the 60GHz band. During the development of this project, we started looking at the use of these bands through Radar-based Communications (publications 1 and 3 in our list in Section 6) and the potential of this band to perform joint communication and sensing activities. Furthermore, this kind of setups would allow for vehicles to be retrofitted and, e.g., make a *legacy* vehicle able to talk to new nodes in the 5.9GHz and the 60GHz+ bands.

The latter point steers us into the direction of our next step in researching connectivity: investigating alternative Access layer technologies and the ability of 802.11bd to perform sensing and Radars for communication purposes. There are open questions regarding beam forming and training, range and stability requirements, communication capacities for future applications, and the effect of sensing and communication on each other's quality.

5.3 Human factors beyond the Dynamic Driving Task

Design decisions will likely affect the strategy used by CAVs. It is possible that automated cars get *driving styles* just like conventional users [16]. This brings another dimension of heterogeneity, since manufacturers market their vehicles to segments as a match to that segment's style. E.g., sports cars are not targeted to "patient and careful" drivers, and A-segment vehicles are not targeted to "thrill-seeking" drivers.

Thus, we can assume that different vehicle classifications and market segments will enable diverging strategies if decision-makers base their design decisions on brand personalities – which in turn can define whether the brand enters the CAV fleet. Therefore, in one way or another, stakeholder decisions will affect fleet behavior inevitably.

One possible solution would be to apply regulations that specify:
1) When automation shall be used (e.g., on E-roads and other controlled-access highways).
2) How automation shall perform (e.g., maximize safety or efficiency in different road conditions).

This, however, is a challenge even in other CCAM scenarios, such as connectivity, where discussions and consensus are hard to achieve.

5.4 Current and future lines of work

In summary, this pre-study has kickstarted the work in several directions. First, regarding Day 3 services and paving the road towards Day 4 by enabling cooperation, we have started a project funded by Trafikverket called *"Here I go" – avancerade funktioner för VRU-medvetenhetsprotokoll i C-ITS*. The project is finishing the first of its two years and work is being performed to enable e-bikes and e-scooters to calculate and share their intended trajectory.

Another line of work takes us into the field of Integrated Sensing and Communications (ISAC) to enable future mobility services with stringent requirements (e.g., platooning, maneuver coordination, collective perception) through the use of Joint Radar and Communication (JRC) and also using natively-networking technologies (e.g., 802.11bd at 60GHz) to perform sensing tasks. We are actively applying for resources to support this research, since preliminary results show that ISAC has the potential to power next generation V2X services while keeping the vehicular spectrum free for existing applications.

6 Dissemination and Publications

How have the results been spread or will be spread?
State the publications published in combination with this project.

Publication 1:

Haller, E., Sidorenko, G., **Amador, O.** and Nilsson, E., 2024. Offloading platooning applications from 5.9, GHz V2X to Radar Communications: effects on safety and efficiency. Presented at the VEHICULAR2024 conference in Athens. Available at arXiv:2401.09242.

This paper assesses the effect of having a large number of connected vehicles sharing the radio medium in future mobility, specifically platooning. Previous work had analyzed network requirements for platooning, and we measure the effect of a fully connected fleet on channel occupancy, network reliability, and thus on platooning (e.g., on inter-vehicle distances, which in turn affects energy efficiency). We then consider the possibility of freeing up medium by offloading intra-platoon communications to Radar-based Communications (RadCom).

Publication 2:

Amador, O., Soto, I., Calderon, M. and Urueña, M., 2023. The Smart Highway to Babel: the coexistence of different generations of Intelligent Transport Systems. Presented at the VEHICULAR2024 conference in Athens. Available at arXiv:2312.13649.

This work presents the effect of having a mixed fleet of connected vehicles on safety metrics such as awareness. In the experimental part, we present that being full-backwards compatible allows for safety-critical messages to reach the whole fleet. However, having even a few legacy vehicles can create problems like network ossification, as it has happened in other network technologies. This paper explores the future issues that stem from having vehicles of different *generations* share the road safely and efficiently.

Publication 3:

Haller, E., Amador, O. and Nilsson, E., 2024. On RadCom channel capacity for V2V applications. Presented at EMC 2024, and available as arXiv preprint arXiv:2405.06482.

This paper addresses the capabilities of proposed technologies (802.11bd in the 60GHz band and RadCom) as enablers for future mobility services such as platooning. It builds upon Publication 1 by calculating channel capacity for 802.11bd @60GHz and RadCom from the communication side for ISAC. Future work on the influence of sensing duty cycles for both technologies is grounded on this work.

Publication 4:
(IEEE IV 2025, prepared to be submitted)
Aramrattana, M., Amador, O. and Haller, E.
On evaluation of risk factors and metrics in Day3+ scenarios

Publication 5:
Amador, O. , Valle F., Sjögren N, Vu D.H., Calderón, M., Soto ,I., and Urueña, M. The Smart Highway to Babel: the Coexistence of Different Generations of Intelligent Transport Systems and Conventional Drivers

Submitted journal extension from Publication 2 including the simulation results for the mix between CAVs and conventional drivers.

7 Acknowledgement

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