Cooperative Connected and Automated Mobility: status and perspectives for Day-2-and-beyond services

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About me: Claudio Casetti

M.Sc. and Ph.D at Politecnico di Torino

Full Professor at ***Politecnico di Torino***
first Italian Engineering School (founded 1859)

He has published over 250 papers on vehicular networks, ITS, 5G/6G networks, IoT systems

Research interests: Connected vehicles, smart mobility, massive IoT, 5G/6G networks

Senior Editor of IEEE Vehicular Technology Magazine

Chaired the Turin Urban Digital Mobility working group within the Smart Roads project fostered by the City of Turin between 2018 and 2022.

Our open-source CCAM simulator: ms-van3t

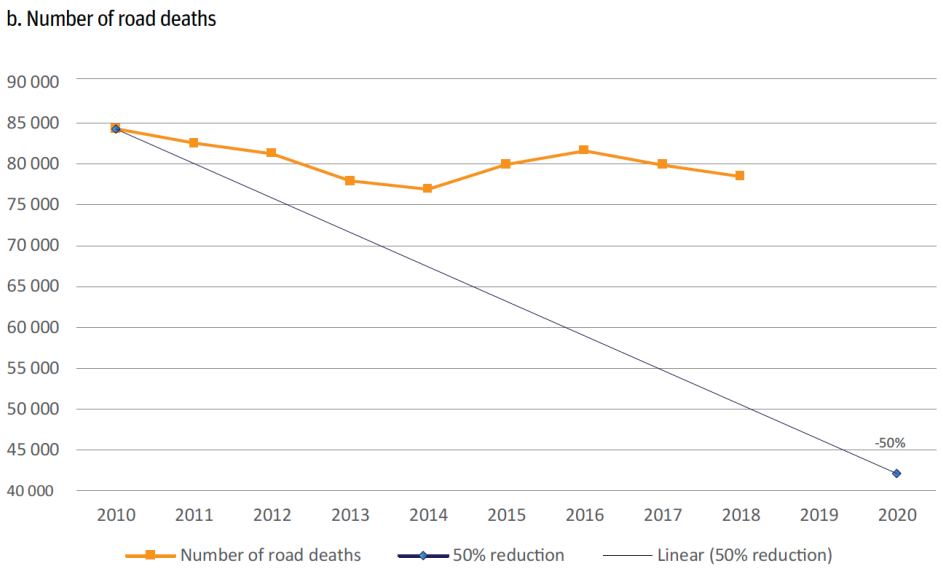
- Available on GitHub with a fully open-source license (GPLv2)
- Quick start guide, software packages and documentation is available at:
  - https://github.com/ms-van3t-devs/ms-van3t
- Designed to run on Linux (Ubuntu 18 to Ubuntu 22) and on Windows 11 with WSL2

Vision Zero

- About **1.35 million people die** each year as a result of road traffic crashes.
- Road traffic injuries are the **leading cause of death among people aged between 5 and 29** years.
- Road traffic crashes cost most countries 3% of their gross domestic product.

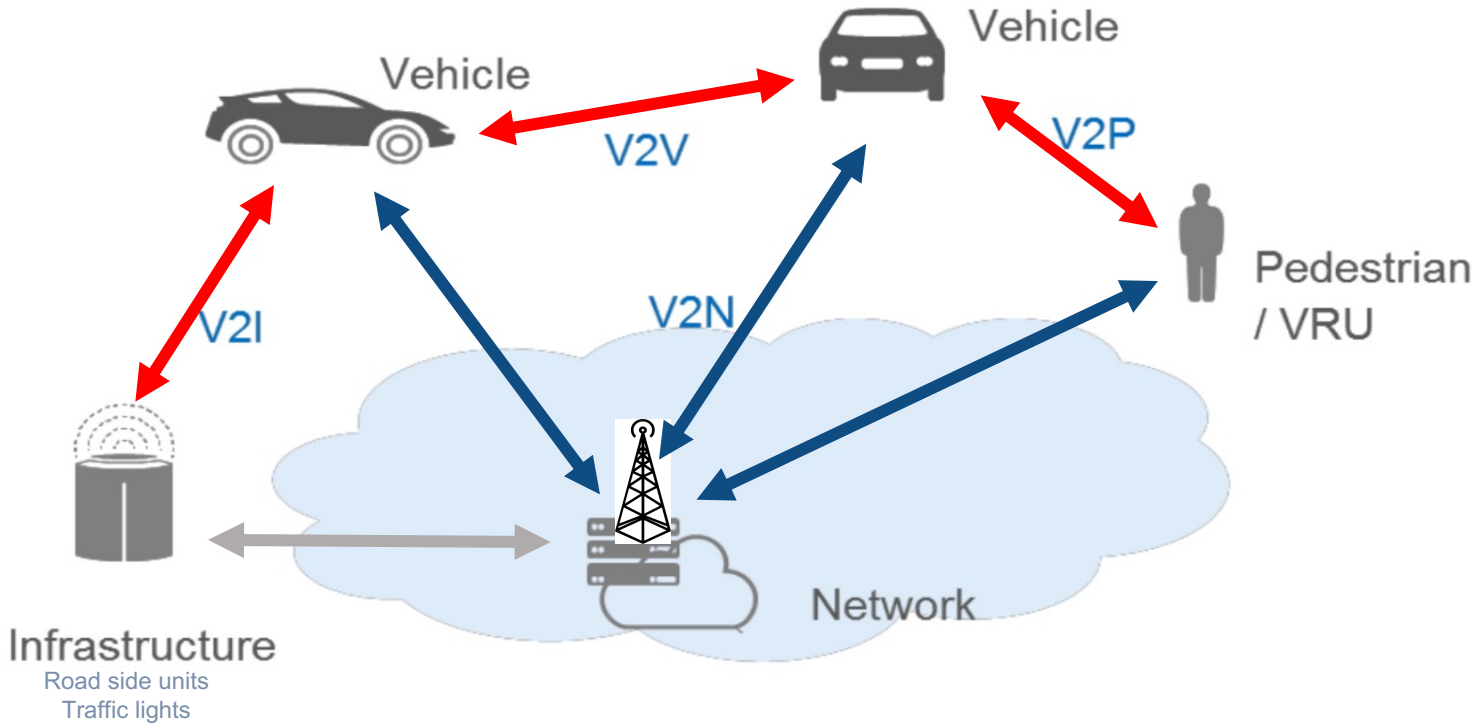
Source: Global status report on road safety 2018, https://www.who.int/en/news-room/fact-sheets/detail/road-traffic-injuries (7 February 2020)

- Deaths are not reducing fast enough



(focus on a group of countries)
Source: International Transport Forum, "ROAD SAFETY ANNUAL REPORT 2020"

Vehicle-to-Everything (V2X)



Cellular or «Long-range», operator licenced bands

Direct or «Short-range», today unlicenced 5.9 GHz band

V2X: two main families

Vehicular Wi-Fi

DSRC/WAVE in the US and ETSI ITS-G5 in the EU

Based on IEEE 802.11p (2010) and IEEE 802.11bd (beginning of 2023)

- Short-range / Direct

Cellular-V2X (C-V2X)

LTE-V2X in the 4th generation (2016/17)

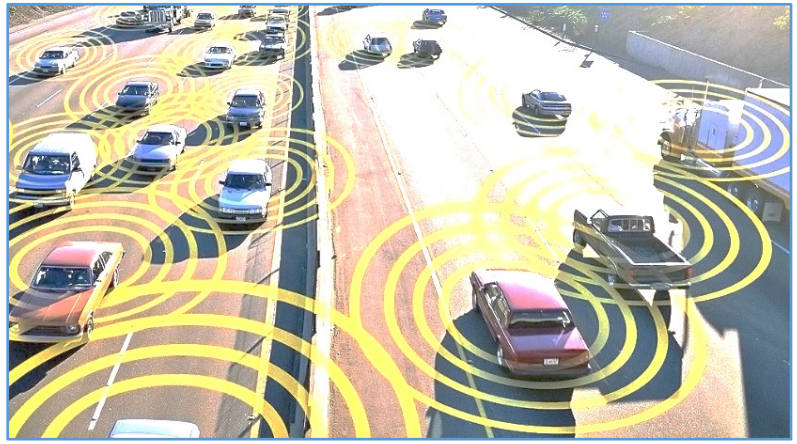
NR-V2X in the 5th generation (2021)

6G-V2X next?

- Long-range / Base stations-based (downlink/uplink)
- Short-range / Direct (sidelink)

Functional perspective: from Day 1 to Day 3+

DAY 1: I share where I am

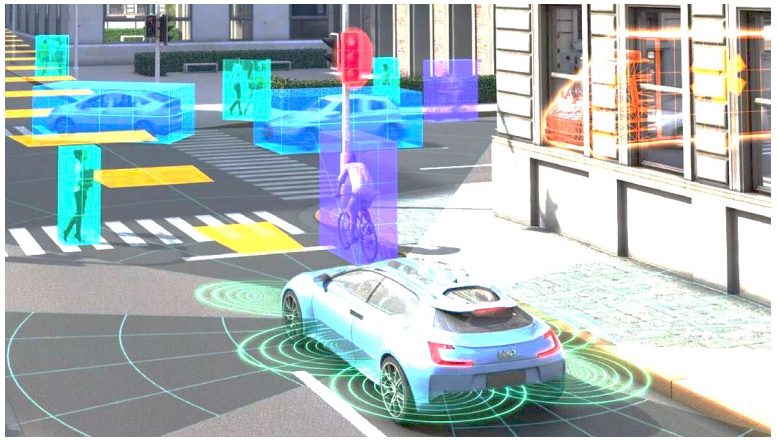


Awareness

Information from vehicles to neighbors about position, speed, direction, etc...
Use CAMs, DENMs.

Already on our roads

DAY 2: I share what I see



Collective Perception

Cars and road-side sensors share what they see

**Years of research,
standards under development**

DAY 3+: I coordinate with the others

Coordinated Maneuvers

All connected, all coordinated, seamless mobility

Research activities undergoing

RESTART MoVeOver

C-CONNECT
CCAM TRUST & RESILIENCE

The ETSI C-ITS Standards

- In Cooperative ITS (C-ITS), vehicles communicate
  - with each other
  - with roadside infrastructure

- Goal: increasing quality and reliability of information about
  - Vehicles
  - their location
  - the road environment
- ETSI provides a “standards Toolbox” for conformance and interoperability testing (“Facilities” layer)

The services beyond Awareness

Collective perception

Vulnerable road user protection

Manoeuvre coordination

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Collective Perception

- Collective Perception (CP): sharing the perceived driving environment of a station based on its on-board sensors
  - Different from Cooperative Awareness (CA)
  - Aims at detecting targets lacking V2X communication capabilities

- Standardization
  - North America (“V2X sensor-sharing for cooperative & automated driving”, SAE J3224)
  - Europe (Collective Perception Service, ETSI TS 103 324 (June 2023) / TR 103 562)
  - China (CSAE 157)

ETSI Collective Perception Service

- Foreseen use cases
  - Detection of Non-Connected Road Users
  - Detection of Safety-Critical Objects
  - CAM Information Aggregation
- Uses CPM (Collective Perception Messages)
  - broadcasted periodically: transmission frequency depending on the detection of new objects and change in their position, speed and heading.

Redundancy Mitigation Techniques

- Problem 1: channel congestion due to multiple vehicle detecting the same object and advertising it
- Problem 2: do on-board sensor have an accurate perception of object?
- Redundancy Mitigation Techniques (RMT) aim at omitting perceived objects if some conditions are satisfied.
  - ✅ less channel load, smaller messages
  - ❌ limited horizon: does receiver truly have a congested channel?
  - ❌ accuracy may be reduced

Redundancy Mitigation Techniques

- Mitigation techniques:
  - Frequency-based
  - Dynamics-based
  - Confidence-based
  - Object Self-Announcement
  - Distance-based

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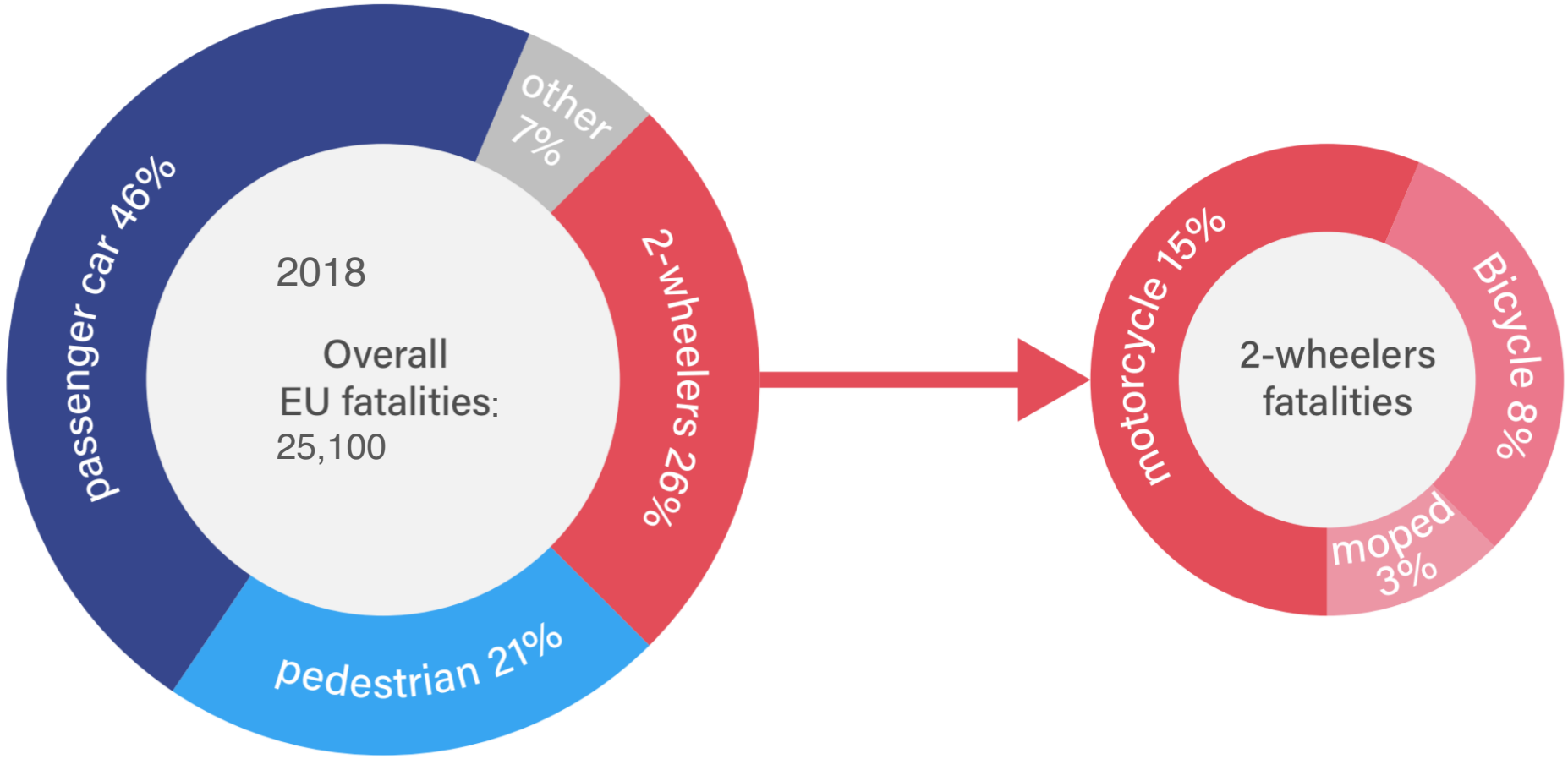
The magnitude of the problem



AVSC Criteria

According to SAE's Automated Vehicle Safety Consortium, VRUs are "any human road user not occupying a vehicle" and should meet three criteria:

1. They are at a higher risk of being injured as a result of a crash than those inside a vehicle who are offered protection from the vehicle and its passive safety systems

2. The range of kinematic parameters governing their motion may be significantly different from on-road vehicles

3. The regulations that govern their interactions with other road users are distinct from on-road vehicles

So, what is a vehicle? What about animals? Or human riding animals (e.g., horse riders)?

Who are Vulnerable Road Users?

	SAE	NHTSA	EU/ETSI	WHO	ISO	IEEE
	X	X	X	X	X	X
	X	X	X	X	X	X
	X	X	X	X	X	X
	X	X				
	X	X			X	
		X	X			
			X			
		X				

Open questions

- Overwhelming effect – too many VRUs?
- Are all VRUs equal?
- Are VRU trajectories predictable like car's trajectories?
- Can VRU predict/interact with driverless cars like with human drivers?
- Effective ways to alert VRUs without distracting them?

Can ITS help?

- VRUs do not stand out easily from the environment
  - Car sensors cannot detect VRUs behind obstacles

⟶ V2X can detect VRUs behind corners, between parked cars, or hidden by other cars.

- VRU motion is not easily predictable
  - Prediction horizon is 3 seconds for pedestrians, 1.5 seconds for bicycles
  - Both late actions and false alarms are highly likely

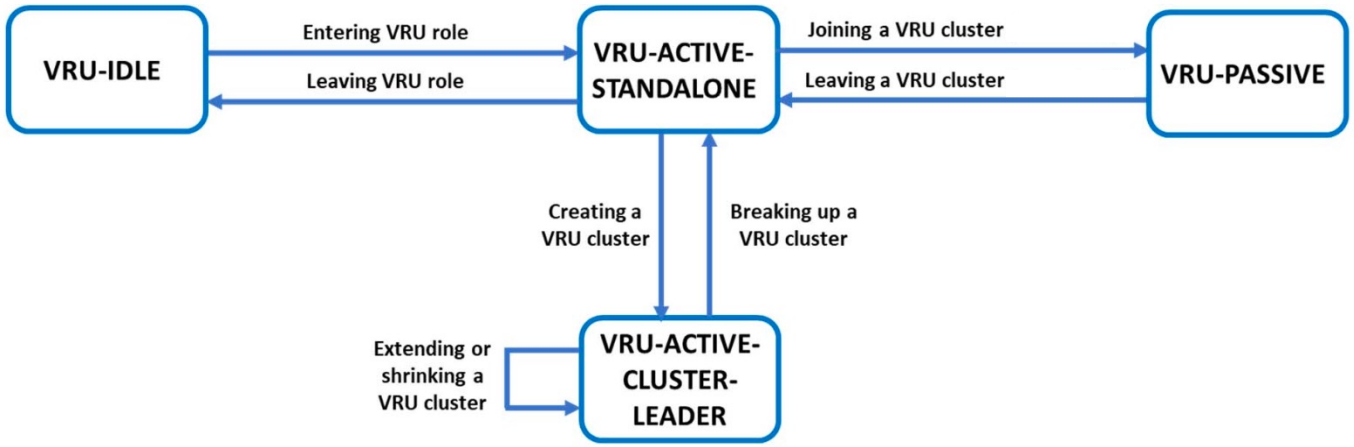
⟶ V2X can provide extremely low latency and data freshness

ETSI ITS-G5 - VAM

- Standards: ETSI TR 103 300-1, TS 103 300-2, **TS 103 300-3** (Feb 2023, VAM format)
- Vulnerable-road-user Awareness Messages (VAM) are transmitted from VRUs
- A VRU shall always use the VAM, while other interfaces including infrastructure and vehicles can use CPM to signal the identified presence of a VRU in the vicinity.
- Profile fits almost all VRU classifications
- Adds clustering functionalities to save resources (e.g., in pedestrian zones, crossings, etc.)
- Messages include motion prediction information:
  - Path history and prediction
  - Safe distance
  - Trajectory change indication (acceleration, heading, stability)

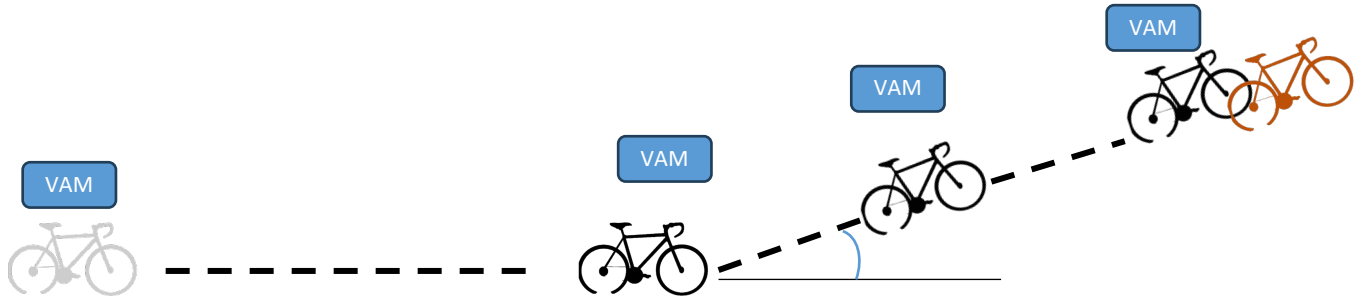
VRU Cluster Operations

- A VRU cluster is considered as a single entity in the overall VRU communication system
- Only the cluster leader transmits cluster VAMs describing entire cluster
  - no. of members, shape of cluster
  - cluster members transmit no VAMs



VAM triggering conditions

- Similarly to CAMs, triggering conditions for VAMs exist:
  - Time elapsed since last VAM
  - Distance since last VAM
  - Speed change
  - Direction change
  - Trajectory interception with other vehicles or VRUs
  - Cluster status change
  - Vehicle closer than Minimum (Lateral/Longitudinal/Vertical) Distance



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Manoeuvre Coordination

- Standards:
  - SAE J3216 (May 2020) - Taxonomy
  - No published ETSI TR yet, final draft TR 103 578 (update July 2023) – Service
- The objective of the Manoeuvre Coordination Service (MCS) is to *exchange information and develop cooperation between ITS-S in proximity or remotely for the support of the driving automation functions of connected cooperative automated vehicles* (CCAV)
- Four classes of cooperation (SAE J3216):
  - Status-Sharing
  - Intent-Sharing
  - **Agreement-Seeking**
  - Prescriptive

Status Sharing

- Communication of a present situation under the form of an object current state or of the result of an event which changed an object state
- Achieved through the exchange of ITS messages:
  - CAMs
  - DENMs
  - VAMs
  - CPMs
- This is a “legacy” situation that does not require MCMs (Release 1 Cooperative Manoeuvering)

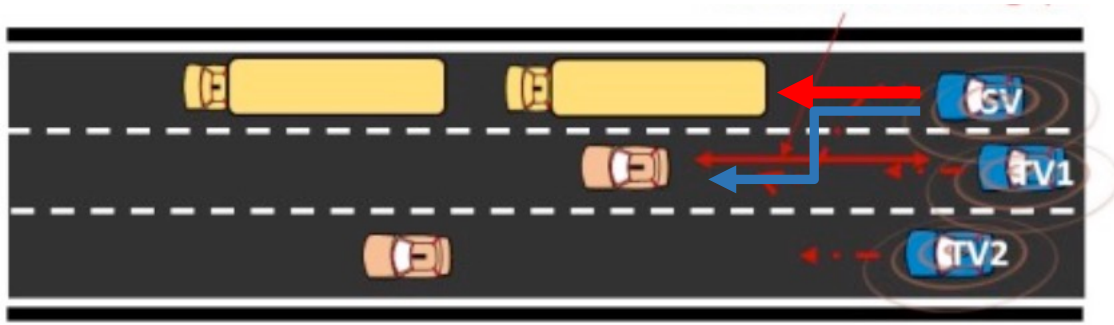
Intent Sharing

- Communication of an intent which will in the future impact the evolution of a mobile object -> PREDICTION
- Can be communicated using visual signals or V2X msg (e.g., CAM)
- Prediction uncertainty level depends on the type of mobile object
  - Automated vehicle
  - Human-driven vehicle
  - VRU

Agreement-seeking

- Manoeuvre achieved by a set of cooperative vehicle in a coordinated manner
- Supported by the exchange of Manoeuvre Coordination Messages (MCM) which however have yet to be standardized
  - Proposals exist from some European projects
- Three use cases are envisioned:
  - V2V cooperation agreement seeking
  - I2V manoeuvres coordination with roadside infrastructure
  - C2V manoeuvres coordination with a central system

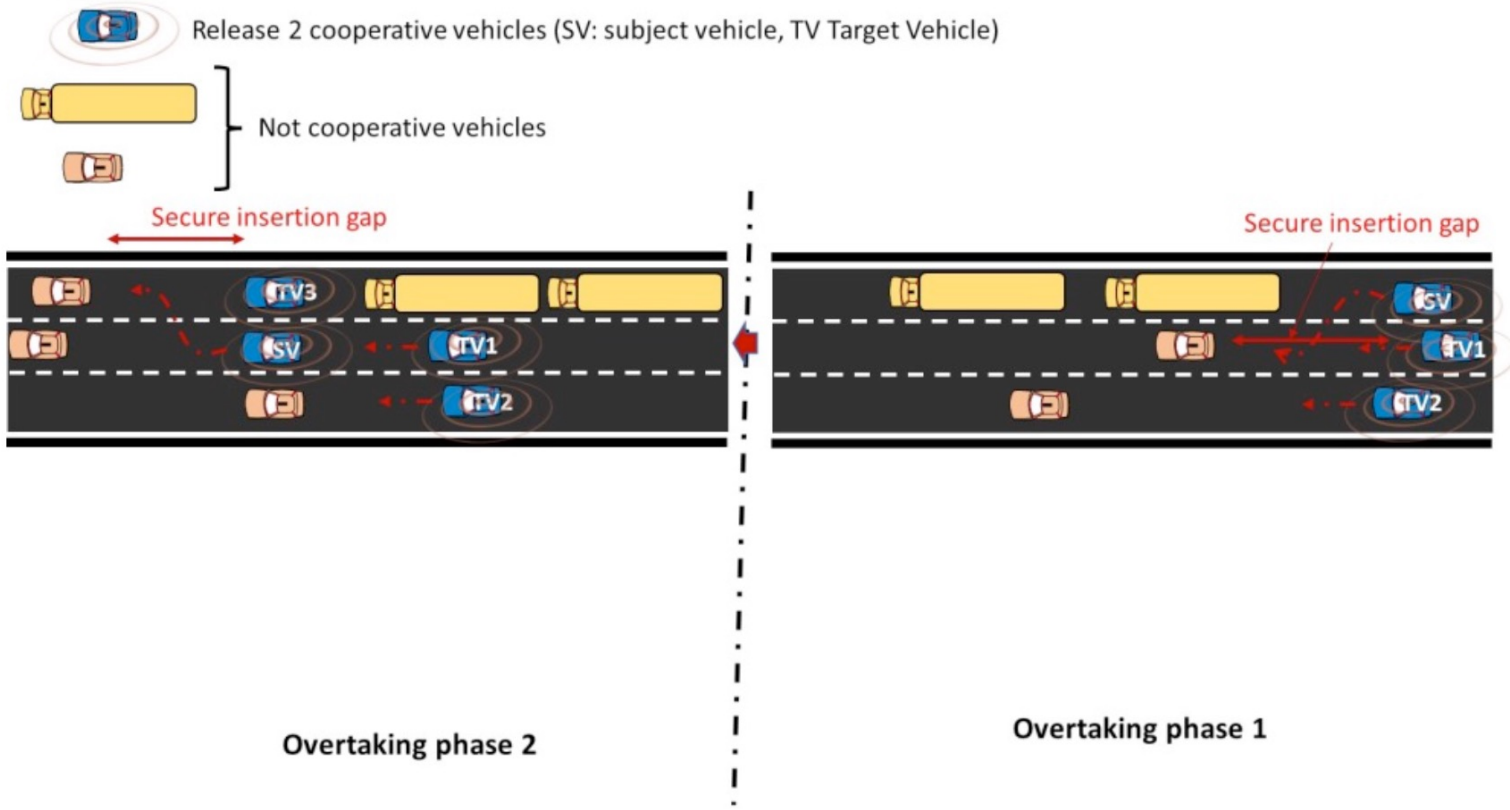
V2V cooperation agreement seeking



- Three cooperative roles
  - *subject vehicle (SV)* disseminates a cooperation request to *target vehicles*
  - *target vehicle (TV)* disseminates a cooperative offer to support one or several *subject vehicles*
  - *relevant vehicle (RV)* impacted by SV and TV, may aid or block them
- Three kinds of trajectories:
  - *Reference* trajectory: The trajectory the vehicle plans to drive currently
  - *Requested* trajectory: The trajectory the vehicle would like to drive but cannot since its necessary manoeuvring space s blocked by another vehicle with higher driving precedence
  - *Alternative Trajectory*: a trajectory that the vehicle would be ready to drive in order to improve another vehicle's situation
- The vehicles inform each other by periodically sending MCMs with their reference/requested/alternative trajectories

V2V cooperation agreement seeking – Example

Lane Change Assistance



Conclusions

- Knowledge of ETSI facilities messages is essential to implement upcoming CCAM service
- Beyond-day-2 service will require a higher degree of coordination among vehicles and other road users
- ETSI actively providing standards
  - Gaps still exist
  - Roadmap accelerating
  - More research is needed