Distributed Intelligence & Technology for Traffic & Mobility Management

State of the art of incentive mechanisms for system optimal behaviour

– Deliverable D2.1 –

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Contents

1 Executive summary

In this report the state of the art of incentive-based traffic management for local bottlenecks is discussed. The purpose is to provide a basis for the theoretical developments in the remainder of WP2, and for the development of the algorithms for the pilot in Bordeaux (Task 7.2). The overall goal of WP2 is to develop incentive-based traffic control approaches for local bottlenecks in the context of various technological settings. This means that not only a traffic control problem has to be solved, but also the proper incentives need to be determined, and that the approach must match the features of the technological environment. Examples of such features are whether the traffic can be measured macroscopically (e.g., queue length, demands) or microscopically (vehicle positions, individual speeds, etc.); whether vehicle trajectories can be controlled on an individual level or macroscopically (as by a traffic light); whether the system can acquire vehicle-based information about vehicle type or value of time; and whether there is roadside technology to enforcement the control measures.

To have an overview of the relevant technologies and methods in the context of incentive-based traffic control, scientific literature in four main areas has been investigated: (1) communication technologies and technological architectures for V2X, (2) data collection and state estimation for cooperative control, (3) control methods for cooperative traffic management at local bottlenecks, (4) incentive schemes for traffic and mobility management.

(1) Communication technologies and technological architectures for V2X are reviewed to get a grasp on the V2X state of the art regarding the following questions.

- What are the recent achievements in the field of V2X communication technologies?

There has been a continuous progress in the field of V2X technologies ever since the original V2X technology (i.e., DSRC) was released in 1999. However, the speed of advancements of V2X communication technologies has increased dramatically since 2013, as it attracted both industrial and governmental funding. As of the start of 2022, there are two mainstream V2X technologies: 802.11 V2X and C-V2X, whose transceivers are now incorporated in newly manufactured vehicles. The state-of-the-art V2X technologies are comprised of C-V2X, further enhanced by 5G-NewRadio-V2X and mmV2X.

- What are the shortcomings of these technologies?

While with each generation of V2X come outstanding pros, there might also emerge some cons that were not present in previous versions. Some notable issues across different V2X technologies include limited coverage range and penetration rate, signal interference, expensive set-up costs, etc.

- What are the technical V2X requirements?

Basic requirements mainly concern safety and warning applications, while advanced requirements concern AI-enabled applications, like cooperative and automated driving and control. Each of these applications require specific latency (bitrate), reliability, penetration rate (line-of-sight), and capacity (throughput) that are discussed in further detail in this chapter.

- What combination of communication technologies can meet these requirements?

The literature recommends the coexistence of different generations of V2X as the way to overcome the shortcomings accompanied in different V2X technologies and meet its basic and advanced requirements. This is expected to lay a solid ground for the real-world implementation of the theories and algorithms that we will develop in WP2.

(2) Data collection and state estimation for cooperative control:

- which sensor and communication technologies (or combinations thereof) are most suitable for realising (cost-) efficient and secure data collection and communication?

Many contributions suggest that a combination of different sensing techniques, onboard and roadside, provide the most promising opportunities to determine information for different cooperative applications cost efficiently.

- Which information is to be exchanged with which vehicles (or road-side systems) at which frequency and aggregation level to achieve the optimal trade-off between information exchange cost and performance of the cooperative vehicle application (e.g., cooperative car-following and lane changing, cooperative intersection control, vehicle routing)?

Different papers take an approach where determining which data is to be exchanged is based on the (projected increase in) performance of the application that uses these data. This bears strong relevance for the information exchange protocols for the system developed in WP2. In the considered literature, reinforcement learning approaches are often used to tackle this design problem.

- Which methods are suitable for optimally estimating and predicting the state of the system, by combining the different available data sources?

The considered literature either uses classical traffic flow theory modelling in combination with filtering techniques or relies on data-driven approaches. While no comprehensive benchmarking papers have been considered, in designing the control approach in WP2 will be pivotal to match the requirements regarding the information stemming from the approach to the filtering method used.

- How to detect anomalies in the data, either by sensor or communication failure or by a security breach, and how to design robust data collection and communication platforms?

This question relates to the issue of security, which becomes important in 'beyond-pilot' applications. We will only briefly consider this topic, mostly highlighting its relevance.

(3) In the discussion of control methods for cooperative traffic management at local bottlenecks the main aspects of controller design are considered: the control objective, the inclusion of policy objectives, the traffic mechanism that is exploited to improve performance, the mathematical formulation of the control problem and its solution, and fairness of and the compliance with the instructed control solutions.

Traffic control approaches can be categorized in approaches that control traffic on a macroscopic level (such as ramp metering controlling the on-ramp flow) and approaches that control individual vehicles in terms of their trajectories. All traffic control approaches aim in the first place at optimizing the overall system performance, such as (a combination of) total travel time, fuel consumption, emissions. In addition, microscopic approaches typically aim to optimize some vehicle-based performance measures too, such as fuel consumption or comfort. The most suitable control approach for incentive-based control seems to be the optimization-based approach, due to its flexibility to use (possibly time-varying) control objectives and constraints. However, due to the relatively high computational complexity, there is a need for approaches that can solve these problems efficiently.

In the transition from the macroscopic control of manual vehicles to the microscopic control connected and automated vehicles there will be a need for more methods that can cope with a wide range of mixed traffic, including manual vehicles and various levels of connectedness and automation. Also, from the perspective of the traffic mechanisms, there is a need to join the macroscopic and microscopic views on traffic control.

In nearly none of the approaches, fairness is considered, neither in the design nor in the evaluation of the controllers. However, typically control at bottlenecks implies the prioritization of some traffic participants, and therefore fairness is an issue. There is an opportunity for incentive-based control to make existing control approaches fairer. The lack of fairness, and the fact that connected and automated vehicles are controlled by advised (requested) trajectories may lead to non-compliance. While compliance for macroscopic controllers is typically ensured by roadside technology and fines, in the incentive-based control context compliance may be ensured by proper incentives (afterwards), but currently there are no theories for the proper pricings.

(4) Incentive survey in incentive schemes for traffic and mobility management, the main questions considered were: What are the fundamental objectives of incentive schemes in mobility management, how are optimal values for (dis)incentives determined, and how can this arbitration be carried out through decentralized decision-making?

Incentive schemes have been employed across multiple levels of the planning pyramid, with objectives ranging from highly strategic (reduce car ownership, promote sustainable modes) to downright operational (buffer traffic outside of an incident area). Across the three axes employed for our literature review evaluation (centralisation/decentralisation, stasis/dynamism and responsiveness/unresponsiveness), a clear trend seems to appear: the closer the objectives are to operational planning, the more the approaches tend to exhibit responsive/dynamic properties. Decentralisation efforts, if present, appear exclusively in operational approaches.

Methods for determining optimal values show considerable dependency on both i) the objectives of interest and ii) whether the (dis)incentive approach is monetary. Considerable research effort has been spent in developing single-objective approaches for monetary disincentive schemes, with optimality guarantees or conditions. Behavioural approaches, such as nudges, have received comparatively less attention in methodological research, although a clear trend for further development of both theoretical and practical applications of these approaches can be observed in the last ~5 years. When considering multiple objectives, potentially conflicting, various approaches have been proposed, ranging from computational heuristics to nonlinear optimization approaches. The issue of pareto-optimality when including directly conflictual objectives (e.g., maximising both efficiency and fairness) remains an open challenge.

Decentralisation remains an unresolved challenge in literature. While some facets of incentive mechanisms are naturally decentralised (e.g., enforcement), we could not identify any efforts in literature concerning either decentralised computation of the optimal (dis)incentive values nor network-wide objective (re)formulation on the basis of decentralised actions.

The fundamental challenge of DIT4TraM is, indeed, filling this gap in literature through the development of innovative management schemes exhibiting decentralisation capabilities reminiscent of swarm intelligence.

2 Survey approach

WP2 deals with decentralised or distributed cooperative control. In this chapter, we summarise the approach we have taken to search for literature on four relevant subjects. Note that instead of providing a detailed state-of-the-art, we decided to first perform a broader literature scan to provide a comprehensive overview of the topic.

2.1 Scope of the state-of-the-art

This report will form the basis for the work in WP2. To this end, we will consider the literature on the following topics:

- Communication technology and technological architectures for V2X. Here, we review the various communication technologies and architectures that are currently in use for V2X (e.g., DSRC or LTE communication). The objective is to identify the technological requirements of V2X and determine whether the state-of-the-art communication technologies can meet them.
- Data collection and state estimation for cooperative control: technological possibilities and requirements. This topic deals with data part of cooperative systems. The chapter looks at the type of sensors that are used, the data which are available, the role data processing, estimation, fusion, and which messages are to be exchanged between vehicles, etc.
- Control methods for cooperative traffic management at local bottlenecks. This topic covers the different control methods for local bottlenecks, and discusses for both conventional and cooperative approaches, the exploited traffic mechanisms, mathematical formulations, and the relations to incentive-based traffic control.
- Incentive schemes in traffic and mobility management. This topic considers incentive or pricing schemes in a broader perspective, looking at topics including but not limited to road pricing, user acceptance, and transportation policy.

2.2 Sources considered

In this review, we have used **Scopus** as the main means to find relevant papers. For each of the topics above, we have considered the between 10 and 30 of the most relevant papers and summarised them in the chapters 3 to 6; the exact number of papers considered is shown in section 2.4.

2.3 Search approach

For each of the topics, we considered the same approach to search for relevant literature. First, for each of the four topics, we formulated a research question. Next, we select keywords (e.g., starting with the research question) that we use in the search, and combine these using logical operators, until we have a set of relevant studies. Using snowballing techniques, we refine the set of papers.

In each of the following chapter, we provide an overview of the sources identified, as well as the keywords, logical operators, etc., used.

2.4 Results overview

Table 1 shows an overview of the number of sources considered for this literature scan.

Table 1 Overview of the survey results per research topic

Topic	Number of papers consider per subtheme
Communication technology	IEEE 802.11 V2X communication technologies [22] C-V2X communication technologies [14] NewRadio (NR) and 5G V2X [7]
Data collection and state estimation	Sensor (and communication) technology [5] Cooperative sensing [3] Message design problem [5] State estimation (and prediction) [8] Data fusion [4] Data security [5]
Control methods	Mathematical approaches for control [5] Freeway onramps and weaving section management [10] Intersection management [13]
Incentive schemes	Management objectives achieved through incentive schemes [7] Monetary incentive schemes [10] Behavioural incentive schemes [7] User acceptance [8]

3 Communication technologies and technological architectures for V2X

WP2 develops theories and algorithms whose real-world implementation would involve a dynamic, complex, and heterogeneous network. Each traffic participant needs to communicate with the Traffic Management Units (TMUs) their real-time positioning along each traffic control section, on top of their preferences. This would result in a huge influx of data to the TMUs on a drastically varying scale, as the number of traffic participants could vary sharply over time and location. Once the TMUs receive this data in full, they need to communicate back to each traffic participant their individualized control advice and the associated payment in next to no time.

Since cooperative driving is a requisite for WP2, we regard Autonomous Vehicles (AVs) as the main candidates for traffic participants, given their capability of safely receiving and carrying out control advice. This is to be enabled by V2I, V2N, and V2V that together (with V2D and V2P) constitute a broader avenue—Vehicle to Everything (V2X) communication technologies that are far from ubiquitous. V2X has emerged to enable vehicles to communicate with their surroundings (e.g., adjacent vehicles, TMUs, etc.) and improve transportation safety and efficiency as a result.

From a broader perspective, for a swarm to occur, each particle needs to have a perception of its own state with relation to the state of its neighbouring particles. In the case of WP2, TMUs represent the particles in the swarm and need to have a certain level of awareness of each other's actions and traffic state before their actions can establish a swarm.

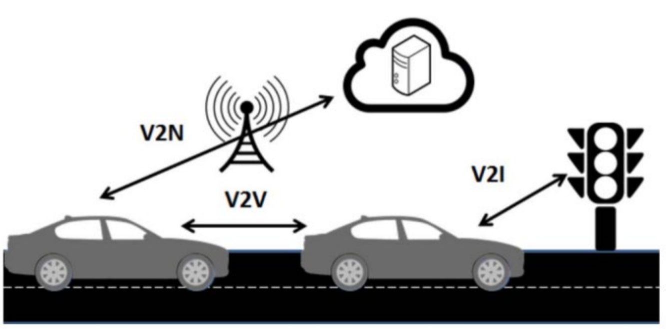

Figure 1 A simple illustration of V2X communications (MacHardy et al. 2018)

Therefore, before WP2 can materialize, a host of technological requirements for V2X must be met—namely ultralow latency, high reliability, seamless wide-area coverage, high-capacity hot-spot, and massive-connections.

Now, 5G-enabled-technologies that aim to support V2X promise meeting these requirements. While the array is promising, we need to investigate and identify V2X communication technologies that are of potential to be employed in WP2. We also need to identify the network architecture that can integrate these heterogeneous technologies to affect the interoperation among multiple coexisting networks.

The main research questions considered in this chapter are: *What are the recent achievements in the field of V2X communication technologies, what are the pros and cons of each of these technologies, what are the technical V2X requirements, and what combination of communication technologies can meet these requirements?*

3.1 IEEE 802.11 V2X communication technologies

Researchers and professionals have been investigating 802.11 V2X to introduce the success of Wi-Fi to vehicular communications. 802.11 V2X is enabled by migrating multiple 802.11 protocols to enhance data communication techniques across vehicles and infrastructure. 802.11 V2X technologies are classified into three types based on diverse spectrum access and use methodologies: DSRC, Wi-Fi, and TVWS.

3.1.1 Dedicated Short-Ranged Communication (DSRC)

DSRC—the original V2X technology—is regarded as the first practical solution for communication among vehicles and roadside infrastructure. It first laid the ground for short-range information exchange between different (i.e., on-board, roadside, or handheld) DSRC devices units in 1999. Through Vehicular Ad hoc Networks (VANETs), DSRC supports a certain level of interoperable services and direct communication for V2I and V2V, and is often deployed to for preliminary road safety applications (such as frontal collision warnings, blind spot warnings, and intersection motion assistance) that rely on frequent exchange of data between different DSRC devices (Kenney 2011). According to the U.S. Department of Transportation (DOT), DSRC is of the potential to reduce U.S. traffic accidents by 82%, which could save both lives and money as significantly (Kenney 2011). Now, it is mandated in North America to equip vehicles manufactured after 2016 with DSRC transceiver.

There are different reserved spectrum bands allocated for DSRC in Europe, North America, and Japan (Abboud, Omar, and Zhuang 2016). In 1991, the U.S. DOT administered a national ITS project in an attempt to employ advanced electronics and communication technologies in the national ground infrastructure, with the objective of improving transportation safety, efficiency, fuel consumption, and pollution (Fang et al. 2017). In 1999, the US Federal Communications Commission (FCC) allocated 75 MHz spectrum in the 5.9 GHz band to support DSRC applications in ITS and V2X, based on the IEEE standard (Std.) 802.11p, which is a revision of the IEEE Std. 802.11a that allows for utilizing the simplicity and capability of distributed operation of 802.11 networks: dynamic spectrum access, quick deployment, and effective network access (Kim and Shrestha 2020).

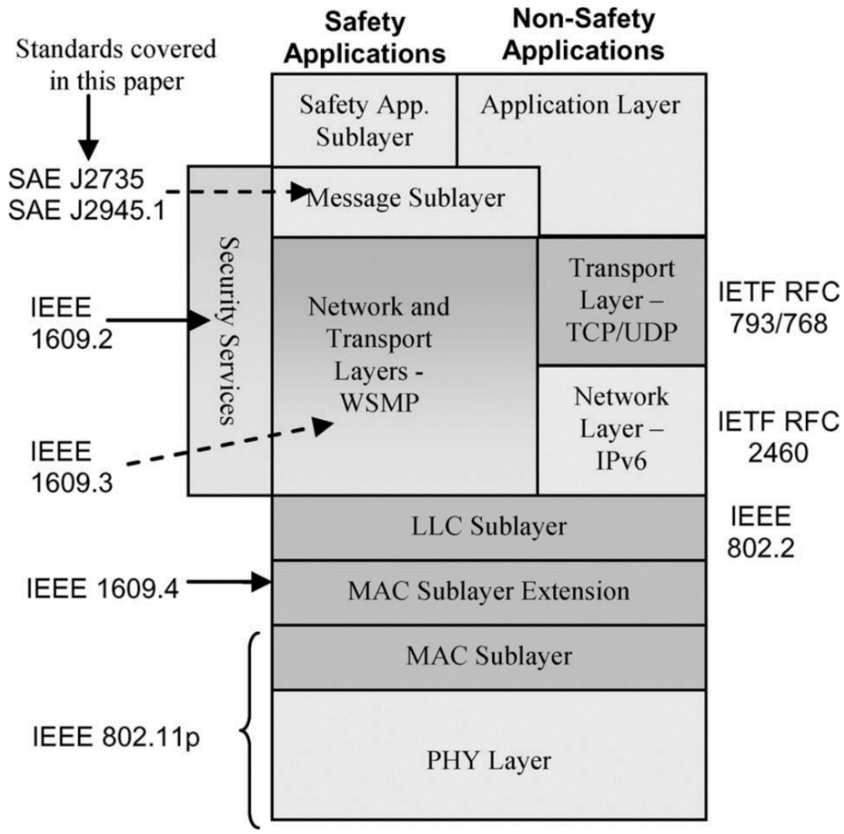

Figure 2 Layered architecture for DSRC communication in the US (Kenney 2011).

Figure 2 shows the layered architecture for DSRC in the U.S. Starting from the bottom, DSRC uses IEEE 802.11p Wireless Access for Vehicular Environments (WAVE), which is an amendment to the IEEE 802.11 (Wi-Fi) Std., to regulate the lower layer wireless connection between physical (PHY) layer and lower Medium Access Control (MAC) sublayer. It employs the Orthogonal Frequency-Division Multiplexing (OFDM) technique to use the dedicated spectrum bands (5.850–5.925 GHz in the United States and 5.855–5.925 GHz in Europe). In the middle of the stack, DSCRC employs a set of IEEE 1609 standards: 1609.4, 1609.3, and 1609.2, respectively for Channel Switching, Network Services (including the WAVE Short Message Protocol—WSMP), and Security Services. DSRC also supports use of the popular internet protocol stacks proposed by the Internet Engineering Task Force (IETF)—i.e., as TCP, UDP, and IPv6 (Kenney 2011).

DSRC alone does not prove the ideal V2X technology for WP2, because its limited bandwidth and communication range do not allow for a sustained transmission of data. Due to the limits of MAC layer access in congested conditions, the latency of access to the DSRC channel can be significant, depending on the application. For instance, (Naik, Choudhury, and Park 2019) established that DSRC can handle end-to-end transmission with a latency of 50–100 ms, which seems adequately fast for managing cooperative connected traffic at local bottlenecks (i.e., WP2) and the current safety applications, but not for some advanced ITS applications, like remote driving, since they demand more stringent rates of data transmission. Notwithstanding its seemingly sufficient rates of data transmission, the connection is frequently interrupted owing to a highly dynamic network structure and Non-Line-of-Sight (NLOS) conditions (Lyu et al. 2018). It is obvious that NLOS is common at local bottlenecks given the varied sizes of vehicles (see Figure 1 for example), rendering DSRC an unfavourable V2X technology to be used in WP2.

Figure 3 NLOS at local bottlenecks, induced by larger vehicles

3.1.2 ISM band Wi-Fi with opportunistic access

Applying the Industrial, Scientific, and Medical (ISM) band Wi-Fi to V2X is predicted to maintain its success, thanks to its unlicensed spectrum advantage and high performance. The literature confirms the utility of Wi-Fi networks by both measurement and analysis (Xu et al. 2017; 2019). (Ott and Kutscher 2004) employed 802.11b at 2.4-GHz Wi-Fi access point to provide road users with the so-called "drive-thru internet", which they showed can attain considerable throughput for both User Datagram Protocol (UDP) and Transmission Control Protocol (TCP) traffic. This system has been used for many data applications, including vehicle data offloading (Y. Chen et al. 2019; Cheng et al. 2016), content caching (H. Wu et al. 2018; Zhou et al. 2019), and data delivery (Zhou et al. 2019).

The coverage range of roadside Wi-Fi networks is limited, resulting in a disruption when leaving the coverage range of one access point to enter that of another. However, this issue can be dealt with by opportunistic Wi-Fi offloading. (Cheng et al. 2014) established an explicit trade-off between the data service delay and the offloading performance by opportunistically transmitting to a succession of Wi-Fi APs along the road (when driving through their coverage ranges).

Wi-Fi has been continuously evolving, which presents quite a few advantages. First, with each generation of Wi-Fi, new technologies are introduced that improve the link rate (Omar et al. 2016). For instance, (Sarvade and Kulkarni 2017) analysed the performance of 802.11p, 802.11n, and 802.11ac MAC protocols in a VANET network for several parameters including throughput, End-to-End Delay, and Jitter. They observed 802.11ac Wi-Fi outperforms the legacy 802.11n protocol in both V2V and V2I communications. Their results suggest that the performance of MAC protocols depends on an array of variables, such as type of mobility, size of the network, distance between communicating nodes, density of nodes, etc. But newer does not necessarily mean better; it depends on the application. For instance, 802.11ac and 802.11n are shown to have better throughput, but with more end-to-end delay and jitter compared to 802.11p. Therefore, 802.11ac and 802.11n is better for non-safety applications—where throughput is more important—and 802.11p is better for safety applications—where message delivery is most important. Overall, 802.11ac Wi-Fi outperforms the legacy 802.11n protocol in both V2V and V2I communications.

Besides the data plane improvement with each Wi-Fi generation, new control functions are also introduced. The 802.11r standard was created to cut down on the number of management frames in the handover process, resulting in a smooth access point switch when driving through different Wi-Fi networks along the road (Sanchez and Boukerche 2016). Hotspot 2.0 has employed AAA features—including automatic association, secure communication, and improved interworking of backhaul networks—in the Wi-Fi and access architecture (Xu et al. 2018). Moreover, Wi-Fi networks are inexpensive to deploy. A roadside access point can be swiftly built with low-cost hardware and open-source software, resulting in the feasibility of establishing a network of Wi-Fi transceivers along the roadside. In an experiment consisting of eight Wi-Fi transceivers along a road segment, (Z. Song, Shangguan, and Jamieson 2017) showed that link quality can be improved significantly for both UDP and TCP traffic.

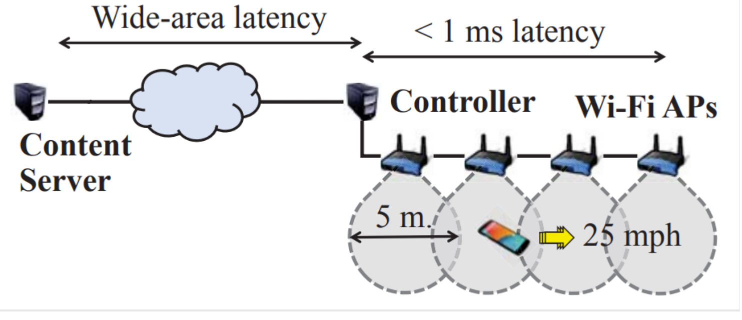

Figure 4 The system architecture for Wi-Fi handover (Z. Song, Shangguan, and Jamieson 2017)

Using Wi-Fi for V2X can have its own downsides due to high mobility, but the pros exceed the cons provided its cost-effectiveness and network performance, and future Wi-Fi generations promise further improvements of link rates, mobility support, and roaming.

3.1.3 TVWS with cognitive spectrum access

DSRC and Wi-Fi both have limited coverage range and penetration rate due to their high carrier frequency (i.e., 5.9 GHz and 2.4 GHz, respectively). However, the TV spectrum between 470 and 790 MHz, which is of a stronger coverage and penetration, is left unused as the Internet has become the main source of media. Therefore, this vacant spectrum can be used in V2X communications to do away with frequent handover and enhance the network bandwidth. The IEEE 802.11af standard was published in 2014 to allow cognitive secondary users to utilize the TVWS frequency (Flores et al. 2013). (Zhou et al. 2017) investigated the feasibility, efficiency, and cost-effectiveness of vehicular access to TVWS by employing the 802.11af TV access system for both V2V and V2I communications (Figure 5), assisted by the geolocation database. While it provides promising advantages, it is made challenging by an array of variables: dynamic TV white space availability with spatial-temporal variation, symmetric uplink/downlink transmit power constraints, high vehicular mobility, and severe vehicular access environments due to increased contention. It is therefore important to devise a more effective multi-tier offloading structure that integrates cellular networks, DSA over TV white space, and Wi-Fi networks to deliver different degrees of broadband access in terms of data throughput and spectrum availability (Zhou et al. 2016). (Ishizu et al. 2014) showed in a field measurement that 802.11af transceivers can achieve a throughput of 15.5 Mbps for downlink and 9.0 Mbps for uplink over 6.3 km.

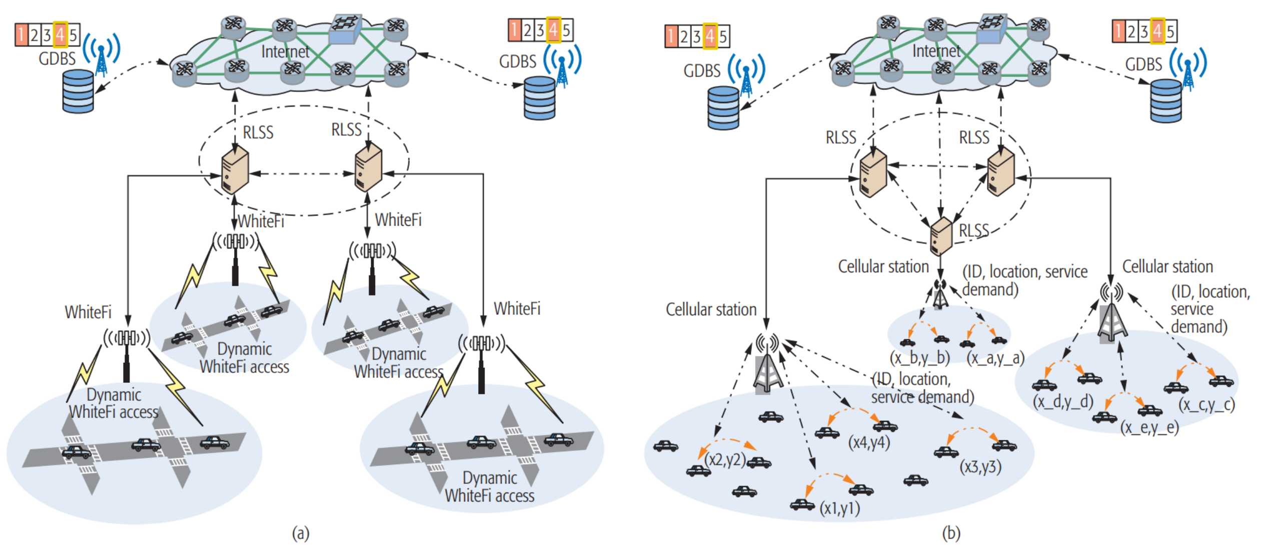

Figure 5 The system architectures for incorporating TV white space in V2I (a) and V2V (b) communications (Zhou et al. 2017)

There are serious issues with employing TVWS access in V2X. First, it is impossible for secondary users to the TV spectrum if primary users occupy it, resulting in the unreliability of the TV band. Second, there would be high number of vehicles accessing the network because the coverage area is quite extensive when compared to normal Wi-Fi networks. This leads to intensive data access contention and severe congestion (Almesaeed et al. 2014). Also, the expensive cost of setting up a TVWS, as well as needing the spectrum permission from the regulation body, further limits the applicability of TVWS in V2X.

3.1.4 The future of IEEE 802.11 V2X technologies

IEEE 802.11 V2X hasn't really proven effective or particularly popular in vehicle industry since its first release, due to concerns across the different kinds of 802.11 V2X: connection interruptions, bandwidth shortages, and coverage limitations. Therefore, traffic management cannot yet enjoy the benefits of cooperative driving and incentive schemes in traffic control. However, these issues can be resolved by employing a combination of features across 802.11 V2X technologies. IEEE has commissioned a Next Generation V2X group to work on including 802.11ac PHY in the next 802.11 V2X standard (Naik, Choudhury, and Park 2019). Modern automobiles are likely to be equipped with several heterogeneous 802.11 V2X radios that can cooperate and interwork together to overcome the aforementioned network performance concerns (Zhou et al. 2016).

To conclude, IEEE 802.11 V2X doesn't seem to meet the WP2 requirements, which motivates moving our attention from the WAVE standard to cellular standard.

3.2 C-V2X communication technologies

Ever since the introduction of DSRC, V2X communication technologies have developed further to attain better pervasiveness, wider-scale, and higher-performance. Besides IEEE 802.11 V2X, Cellular-V2X (C-V2X)—standardized and designed by the 3rd Generation Partnership Project (3GPP) for automotive services—is now regarded as another prominent V2X technology. In this subsection, we review the stages wherein 3GPP has upgraded C-V2X, its technical requirements and how to meet them, and the literature on its performance.

3.2.1 C-V2X evolution phases

As shown in Figure 6, 3GPP has developed C-V2X in 3 phases that are as follows.

Phase 1: LTE has been employed for basic V2X applications like Cooperative Awareness Message (CAM), Decentralized Environmental Notification Message (DENM), and Basic Safety Message (BSM) since the 3GPP 14 was released in 2015. 3GPP has specified 27 use cases that cover V2N, V2I, V2V, and V2P applications. It has been substantiated that V2X applications can be handled over Uu interface-based LTE networks, and help attain an efficient resource allocation and selection service, an upgraded physical layer, and synchronization services (Fallgren et al. 2021).

Phase 2: Rel-15 incorporated enhancements to accommodate V2X advanced scenarios such as remote driving, vehicle platooning, expanded sensors, and automated driving (Lee et al. 2016). It offered some new features while remaining compatible with Rel-14: certificate authority for mode-4, radio resource pool sharing across mode-3 (centralized) and mode-4 (decentralized) user equipment, reduced time between packet arrivals at Layer, TTI shortening, and resource selection. In addition, 3GPP has recently begun working on 5G New Radio V2X (NR-V2X) to establish performance measurements, simulation scenarios, channel modeling, and spectrum to assess improved V2X applications (AbdelHakeem, Hady, and Kim 2021).

Phase 3: 5G Automotive Association (5GAA) and Next Generation Mobile Networks alliance (NGMN) have developed V2X solutions to cover road safety and connected cars (Haidar, Kaiser, and Lonc 2017). We will further explore 5G in the next subsection.

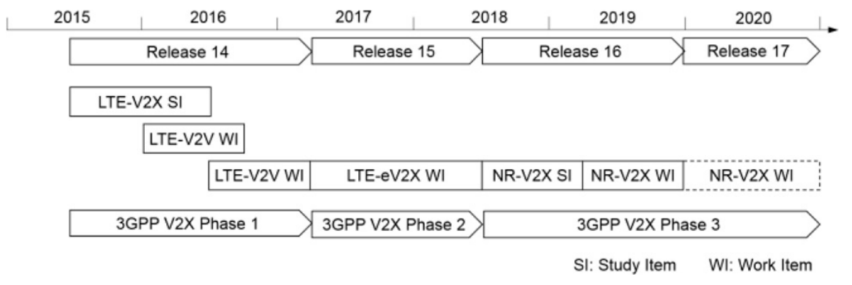

Figure 6 Timeline of 3GPP C-V2X standardization (S. Chen et al. 2020)

3.2.2 C-V2X technical requirements

(3GPP 2015b) has defined the major requirements to support V2X applications, which are as follows:

1. transmission latency should be less than 100 ms, and for the safety applications, this number should be below 20 ms;
2. message transfer frequency should be 50 Hz, and for typical cases, this number can be 10 Hz;
3. vehicle speed should be supported up to 500 km/h;
4. communication range;
5. V2X communications should be supported in and out of network coverage.

Table 2 PERFORMANCE REQUIREMENTS FOR THE BASIC AND ADVANCED V2X SERVICES (S. Chen et al. 2020)

Use case group	Transmission mode	Latency (ms)	Reliability	Maximum Data Rate (Mbps)	Communication Range (m)
Basic road safety services supported by 3GPP Rel-14/Rel-15	Broadcast	10-100	90%	31.7	100-300
Vehicles Platooning	Broadcast, groupcast and unicast	10-25	90% - [99.99%]	[65]	less than 100m; [5-10] sec * max relative speed
Advanced driving	Broadcast	[3-100]	[99.99%]-[99.999%]	[50]	[5-10] sec * max relative speed
Extended sensor	Broadcast	3-100	[90%-99.999%]	1000	[50-1000]
Remote driving	Unicast	[5-20]	[99.999%]	UL: 25 DL: 1	Same as cellular uplink and downlink

3.2.3 Centralized/Distributed Architecture and Communications

To meet C-V2X technical requirements, LTE-V2X incorporates two complementary transmission modes, LTE-PC5 and LTE-Uu (Figure 6):

1. LTE-PC5: The LTE-D2D technology supports V2X communication via the PC5 interface by means of sidelink. V2X data flow can be offloaded from the infrastructure by supporting direct communications among users in a decentralized manner. As a result, higher network throughput, reduced

energy consumption, greater spectrum utilization, and lower delay performance is attainable. V2X communications over the PC5 interface, unlike DSRC, can employ either network planned mode (centralized) or user equipment autonomous selection mode (decentralized).
2. LTE-Uu: For V2X communication to be supported over the LTE-Uu interface user equipment needs to be inside network coverage. While transferring V2X data through uplink, the user equipment might receive V2X data via downlink unicast or multimedia broadcast/multicast service delivery. Compared to 802.11p, transmissions over LTE-Uu are scheduled by a network scheduler in the eNodeB that effectively controls collisions and mutual interference. Depending on the priority and bitrate/latency requirements for each V2X application, the scheduler guarantees the minimum quality of service for different applications by admission control and radio resources allocation. This is a significant asset compared to the Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA) scheme in 802.11p.

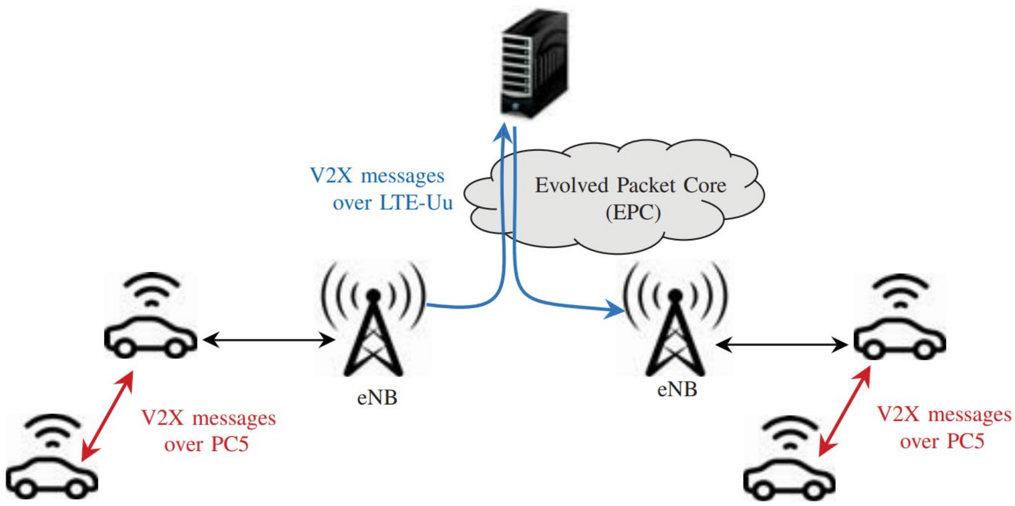

Figure 7 LTE-V2X architecture (Karoui, Freitas, and Chalhoub 2020)

The LTE network, however, isn't developed and optimized ideally for sending huge quantities of extremely tiny packets in V2X use cases, as it was meant for mobile broadband. Therefore, there are issues with its use for V2X like control and channel estimate overhead, resource granularity, and channel coding, among others. Considering the heavy load of V2X traffic in dense areas or during peak hours, serious latency will be caused without the congestion control scheme. Without a congestion control strategy, substantial delay will be created by the tremendous load of V2X traffic in congested regions or during peak hours. Furthermore, LTE device-to-device can only be used for public safety services in low-mobility environments, because it is incapable of meeting the strict reliability and latency requirements of V2V communications in high-speed settings; the fast and frequent handover, as well as the rapid change of network topology makes it challenging to guarantee the minimum quality of service for V2X (Lyu et al. 2019).

To help meet the V2X requirements for device-to-device communications, the (3GPP 2015a) Radio Access Network (RAN) group has proposed upgrading sidelink in LTE from the following aspects:

1. PC5 Interface: To enable V2V applications using the LTE-PC5 interface, the physical layer structure, resource allocation, and synchronization of the LTE sidelink should be improved.
    a. Pilot Design: Due to strong Doppler frequency shift, the current LTE can only serve device-to-device communications in static or low-mobility environments, and not in the high-mobility environments for which LTE-V2X runs at a higher spectrum band (than 5.9 GHz). The Demodulation Reference Signal (DMRS) is reused in LTE-V2X, and each frame of 1 ms contains four DMRS, which can be used in high-mobility conditions like WP2. In each physical channel, SC-FDM is used to provide V2V transmission.
    b. Resource allocation: In PC5-based V2V, transmissions are governed by the scheduling assignment. LTE-PC5 uses a semi-persistent transmission scheme to handle periodic V2X messages with lengthy duration times. Centralized or distributed scheduling can be used to configure user equipment resource selection. A user equipment may determine which resources will be occupied and/or clashed by other user equipment, allowing it to avoid clashing resource allocations for its transmission. The resource allocation technique is tailored to avoid collisions and increase dependability due to the huge number of vehicles within a cellular cell.
    c. Synchronization: When the vehicle user equipment runs on PC5 V2V, its reference signal can be Global Navigation Satellite System (GNSS), eNodeB, or other user equipment. When the user equipment is not covered by eNodeB, GNSS takes precedence; otherwise, the user equipment can choose between the two, increasing the synchronization reliability.
2. Uu Interface:
    a. Uplink/downlink Transmission Enhancement: When a lengthy scheduling request period (e.g., more than 10 ms) is employed, the E-UTRAN cannot fulfil the delay requirement for V2X service via the Uu interface. To enable Uu V2V, user equipments should be set with a shorter scheduling request time (such as 1 or 10 ms). But this will undesirably raise the uplink overhead, particularly when a cell contains numerous vehicles (e.g., in

cities or when Uu resources are shared with other services). Therefore, it is recommended to employ uplink semi-persistent scheduling to curb uplink overhead, and the semi-persistent scheduling period should be substantially shorter than the latency requirement of 100 ms. The user equipment may also be able to aid the eNodeB in effectively controlling the uplink semi-persistent scheduling. Downlink transmission provides small area broadcast, low-latency single cell point-to-multi-point transmission (SC-PTM), and Multicast/Broadcast Single-Frequency Network (MBSFN) in the context of V2X. Also, LTE-V2X allows for local deployment of the core network element and establishes specific V2X quality of service to ensure decent transmission performance.

b. Multi-access edge computing (MEC): LTE-V2X uses MEC technology to meet the ultra-reliable low-latency transmission needs of V2X (such as cooperative, connected, and autonomous driving). The 3GPP has investigated the major issues such architecture, service management, and mobility management.

To conclude, LTE-V2X paves the way for 5G and can interoperate with IEEE Std. 802.11p in adjacent channels. So, LTE-V2X is a tough competitor for IEEE 802.11p V2X that combines LTE-4G with device-to-device communication and will evolve to 5G NR-V2X. For a better highlight the benefits of LTE-PC5 R-14 on DSRC, Table 1 compares the two technologies.

Table 3 Comparison Between LTE-V2X PC5 and DSRC (5GAA 2016)

	C-V2X: PC5	802.11p	C-V2X: PC5 Advantage
Synchronization	Synchronous	Asynchronous	Spectral Efficiency. Synchronization enables time division multiplexing (TDM) and lowers channel access overhead.
Resource Multiplexing Across Vehicles	FDM and Time Division Multiplexing (TDM) Possible	TDM Only	Frequency Division Multiplexing allows for larger link budget and therefore longer range – or more reliable performance at the same range.
Channel Coding	Turbo	Convolutional	Coding gain from turbo codes leads to longer range – or more reliable performance at the same range.
Retransmission	Hybrid Automatic Repeat Request (HARQ)	No HARQ	Leads to longer range – or more reliable performance at the same range.
Waveform	SC-FDM	OFDM	Allows for more transmit power with the same power amplifier. Leads to longer range – or more reliable performance at the same range.
Resource Selection	Semi-persistent transmission with relative energy-based selection.	Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA)	Optimizes resource selection with selection of close to 'best' resource with no contention overheads. By contrast 802.11p protocol selects the first "good enough" resource and requires contention overhead.

3.2.4 C-V2X performance

There aren't many works available on C-V2X performance, since it's rather a new technology. The majority of the existing research is carried out using simulation. Ghosh (2018) demonstrated that the performance of C-V2X sidelink mode 4 outperforms that of DSRC in the link budget, which (Sakaguchi et al. 2017) has substantiated in real-world applications. (Mavromatis et al. 2018) confirmed a better performance from improved spectrum use when employing sidelink mode 3 centralized resource control in C-V2X. However, according to (Islam, Kim, and Kwak 2015), when traffic density rises, C-V2X performance suffers owing to interference caused by frequency reuse in C-V2X mode 4, which reduces reuse distance.

3.3 NewRadio (NR) and 5G V2X

In 2020, vehicle manufacturers announced their first commercial launch of cars equipped with C-V2X, establishing 2020 as the landmark for the uptake of Connected Automated Driving (CAD). This paves the way to cooperative, fully automated driving, and 5G is anticipated to power this transition, given its outstanding performance in terms of coverage, throughput, latency, redundancy, and reliability. Therefore, we regard 5G as the prospective communication technology to rely on in WP2.

While 5G has evolved from the LTE mobile 4G, they are different in several aspects. For instance, 4G relies on many high-power base stations to transmit signals over long distances, whereas 5G relies on a large number of small base stations that support millimetre wave transmission in the 30-300 GHz range and are quite versatile in terms of where they can be installed, thanks to their size. More importantly, 5G signals can travel short distances and are unaffected by weather and structural impediments (Naik, Liu, and Park 2018).

To support ultra-reliable communications through ultra-low latency and ultra-high throughput, 5G introduces several new features. For instance, through D2D, 5G presents new services like Proximity Service (ProSe), an important feature that provides awareness of surrounding devices and services based on locality data. Additionally, SDN data management, cloud computing, and basic network topology and structure are other services provided by 5G.

3.3.1 Coexistence of NR-V2X and C-V2X

5G is backwards and forwards compatible thanks to 3GPP's work on LTE-Advanced and LTE-Pro (Boban et al. 2017), and will employ the air-interface. Besides PC5 and LTE-Uu, 3GPP introduced NR standardization as the first phase of 5G-enabled enhancement for C-V2X, supporting massive connectivity with a high reliability.

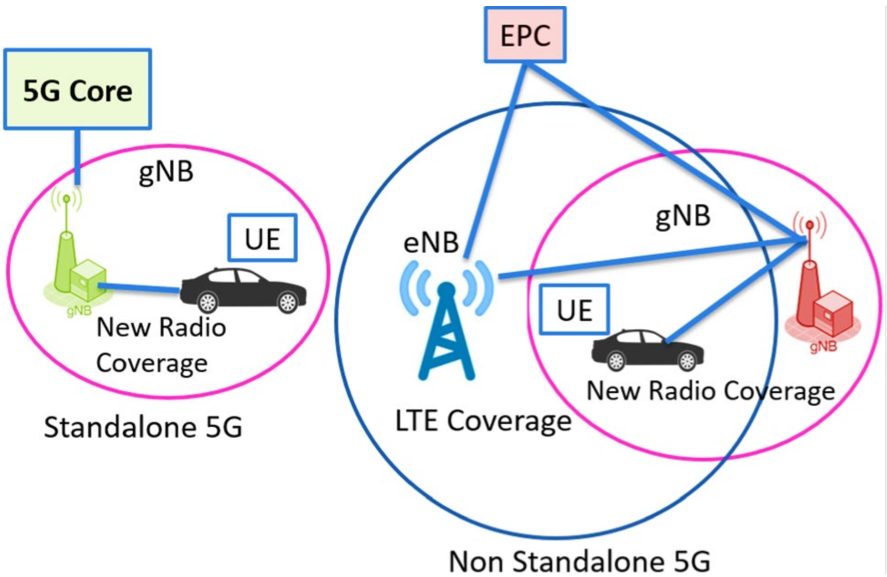

Figure 8 5G-NR standalone and non-standalone modes (Hakeem, Hady, and Kim 2020a)

5G works in two modes: non-standalone and standalone (Figure 8). The non-standalone mode is the 5G primary mode wherein devices are attached to 5G-

NR core network and transmit signal to the Evolved Packet Core (EPC) either directly or through 4G base stations. Whereas in the standalone mode, devices transmit data directly to 5G core network, using a 5G-NR interface. The standalone mode supports user plane facilities and full control through a 5G core network.

5G-NR needs to coexist with LTE coverage, not only in neighbouring bands, but sometimes inside the same frequency band (as shown in Figure 9). 5G NR bandwidth components allow 5G NR and LTE signals to coexist on the same carrier, which can pose additional signal interference challenges owing to overlapping and sometimes closely spaced transmissions.

3GPP is currently working on the compatibility of future releases of 5G-NR with the current ones, so that they can be seamlessly integrated. By combining licensed and unlicensed spectrum frequency bands, 3GPP wants to enhance the scalability, performance, and flexibility of wireless communications.

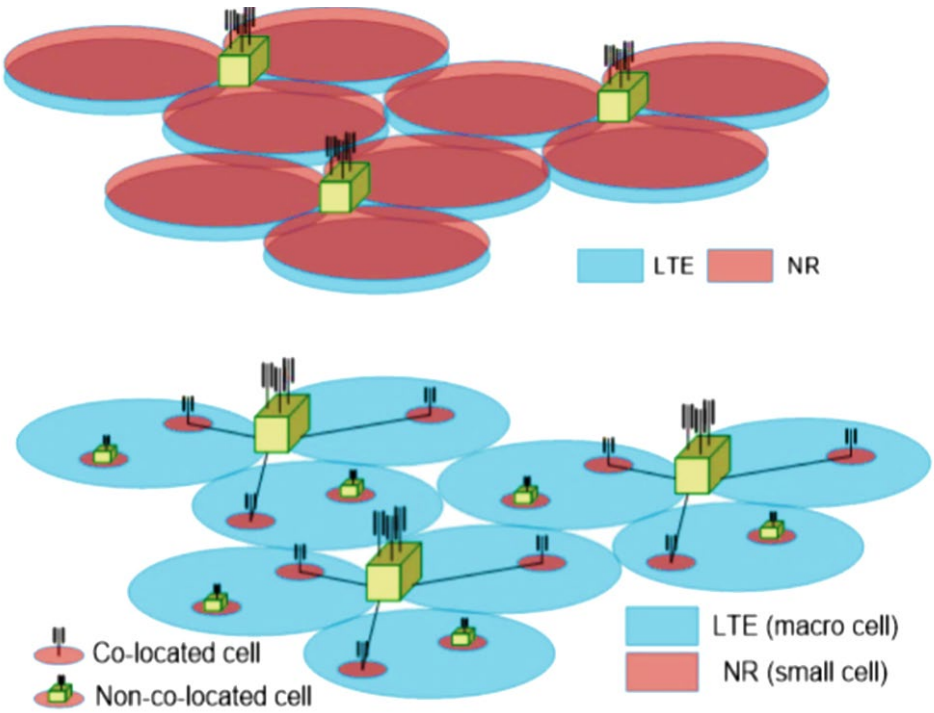

Figure 9 Coexistence of 5G-NR and LTE in terms of cell coverage (Hakeem, Hady, and Kim 2020b)

NR-V2X is not going to replace C-V2X because C-V2X is currently in commercial usage, but it is coming to help C-V2X support use cases with advanced requirements that cannot be met by C-V2X. Therefore, car manufacturers should enable their cars to use both NR-V2X and C-V2X simultaneously. This way, C-V2X will handle use case circumstances that it can reliably support, and NR-V2X will take care of circumstances where C-V2X cannot be relied on.

In addition to basic safety requirements that are currently met by C-V2X, NR-V2X aims to meet the advanced requirements of V2X. As a result, it is expected to possess a certain level of reliability to manage circumstances with variable latency, traffic, and throughput. The variability of these elements is due to the distinct requirements of different use cases, as some require periodic messaging, while others require aperiodic traffic.

NR-V2X will use either unicast or group cast to communicate with vehicles depending on the use case, i.e., whether it's one vehicle that needs to be addressed, or a group of vehicles (as the names, unicast and group cast, suggest).

Currently NR-V2X pursues the following objectives:

1. Enhancing the Uu interface to accommodate the more complex requirements of some V2X applications.
2. Investigating ways to choose the optimum Radio Access Technology (RAT)/Interface for every message transfer.
3. Enhancing the sidelink design to accommodate advanced V2X needs.
4. Enhancing the NR Uu interface for sidelink resource configuration and allocation.
5. Studying the feasibility of and technical solutions for the coexistence of C-V2X and NR-V2X.
6. Studying technical solutions to make NR-V2X capable of supporting variable levels of quality of service, from basic to ultra-high, across different radio interfaces.

3.3.2 Millimetre Wave (mmWave) technology

The mmWave radio technology is seen as a promising component of the forthcoming 5G network. Low latency and more high-speed data are enabled via the sub-6 GHz band and mmWave, which are both represented in 5G. The mmWave allocates a specific part of the wireless spectrum within the range of (24–100) GHz, as lower frequencies are crowded with TV, radio, and LTE transmissions. A short wavelength is used to transfer data faster, however it only works over short distances. The purpose of mmWave is to increase data-bandwidth accessibility in densely populated places. The sub-6 GHz band, on the other hand, can play an important role in providing reliable and continuous coverage across extended distances such as cities and villages (Shimizu et al. 2018).

The mmWave is a critical technology for meeting the advanced requirements of 5G autonomous driving applications, and reliably support the following V2X use cases:

- V2V: mmWave will support communication of sensory information in dense traffic scenarios such as platooning, cooperative lane change, and sensor-sharing by allowing communication among all surrounding cars using PC5 interface based LTE or NR.
- V2I: mmWave will support the transmission of large amounts of data, such as object recognition and detection information through a short, timeless message.

5G signals are extremely high-frequency and do not travel long distances or transfer well from inside to outside. However, because to beamforming and massive MIMO technologies, a strict line-of-sight requirement is no longer required to deploy millimeter-wave technology. MmWave transmissions may not be able to penetrate buildings or obstructions, but they can skip around them to ensure a decent 5G service. During rain, millimeter-wave signal strength decreases marginally, resulting in slightly slower speeds and connection issues. Due to the short small coverage of mmWave base stations, several base stations need be deployed closely together to cover the radius covered by one LTE base station (Shimizu et al. 2018).

3.3.3 5G-V2X architecture and functionalities

In this section, we go through the 5G-V2X architecture (Figure 10) and functionalities as defined by the 5GCAR project and 3GPP recommendation. We also go through the fundamental implementations that will have an impact on the future of V2X communications.

Fifth Generation Communication Automotive Research and innovation (5GCAR) is a Horizon 2020-funded innovation research project that aims to implement and test 5G-V2X networks (Fallgren et al. 2021). The 5GCAR project is one of the most important 5G designs since it proposes methodologies, protocols, and network designs to improve V2X communication utilizing 5G. As a member of the ongoing 3GPP standardization, 5GCAR's main objectives are to reduce end-to-end latency, improve network resilience, assure high network availability, enable radio access technology compatibility, and boost enormous access scalability while maintaining network security. 5G positioning, 5G radio resource management, multi-RAT methods, management of 5G mobility, 5G-V2X Slicing, Privacy, and Security are all critical components of 5GCAR.

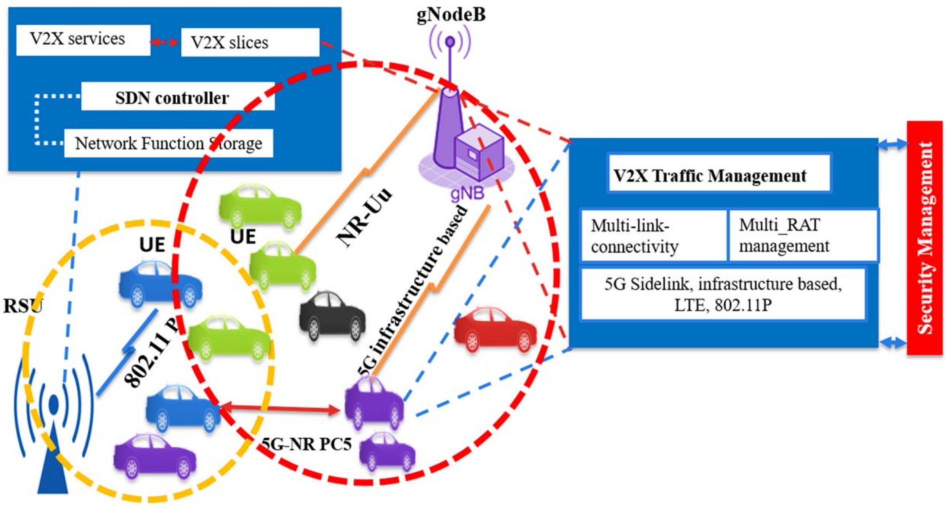

Figure 10 End to end 5G-V2X architecture (Hakeem, Hady, and Kim 2020a)

Network Management

Management, multi-connectivity, security, and edge computing are all part of the 5G-V2X network architecture. Every key action for effective and practical deployment and self-regulation of the fundamental V2X services is included in network management. 5GCAR defines Infrastructure-as-a-service (IaaS) as a key definition for active system management. Critical V2X services are deployed according to the geographic locations of cars using Network Function Virtualization (NFV) and SDN technologies (Sahin et al. 2018). V2X networks are seriously affected by security issues. As a result, it's been extensively researched in previous V2X technologies, such as DSRC technology. By employing the security process at the user equipment's application layer while exploiting the current network connectivity, the 5GCAR project provides two distinct techniques for the 5G-V2X security and integrity check for messages, respectively.

Multi Connectivity

V2X apps are expected to connect via infrastructure radio links (Uu) and direct PC5 links that have distinct characteristics from each other. It is believed that V2V sidelink communication will provide accurate resource allocation, extensive out-network coverage, and low latency. The WAN (Uu) interface, on the other hand, is thought to deliver high-reliability and high-throughput. 5GCAR asserts to meet the V2X network requirements with only one type of communication link. In addition, 5GCAR studied a system with many RATs, which might broaden the existing problems, provided that each RAT method has its unique set of properties.

Network slicing and Edge computing

To promote V2X use cases, network-edge computing capabilities are substantial advancements. Many enhancements in RAT are required to fully utilize edge computing capabilities. When a vehicle is expected to switch between separate base stations linked to different management edge servers, the current jobs are often given to the newly attached server to reduce the work time delay caused by the handover. 5GCAR outlined various ways for integrating edge computing with mmWave technology in order to maximize the use of available radio resources while lowering the overhead of performing operations. Network slicing is a critical enabler for delivering a wide range of autonomous services using a shared infrastructure. Because of the heterogeneity of 5G network slicing, vehicles can be linked to several network slices at the same time. A single V2X use case suggested by a distinct operator can be served by each slice (Kaloxylos 2018).

3.4 Conclusions

In this chapter, we comprehensively reviewed state-of-the-art communication technologies used in V2X. We recap our findings with regards to the questions that we aimed to answer through this review. These questions are as follows:

- What are the recent achievements in the field of V2X communication technologies?
- What are the shortcomings of these technologies?
- What are the technical V2X requirements?
- What combination of communication technologies can meet these requirements?

Looking back at the history of V2X development to answer question 1, we reviewed different V2X communication technologies, ranging from DSRC to 5G-NR-V2X, each with its own architecture. There has been a continuous progress in the field of V2X technologies ever since the original V2X technology (i.e., DSRC) was released in 1999. However, the speed of advancements of V2X communication technologies has increased dramatically since 2013, as it attracted both industrial and governmental funding. As of the start of 2022, there are two mainstream V2X technologies: 802.11 V2X and C-V2X, whose transceivers are now incorporated in newly manufactured vehicles. The state-of-the-art V2X technologies are comprised of C-V2X, further enhanced by 5G-NewRadio-V2X and mmV2X.

Regarding question 2, a perusal on the literature implies that newer does not necessarily mean better. While with each generation of V2X come outstanding pros, there might also emerge some cons that were not present in previous versions. Some notable issues across different V2X technologies include limited coverage range and penetration rate, signal interference, expensive set-up costs, etc.

With respect to question 3, the literature categorizes V2X technical requirements as basic and advanced. Basic requirements mainly concern safety and warning applications, while advanced requirements concern AI-enabled applications, like cooperative and automated driving and control. Each of these applications require specific latency (bitrate), reliability, penetration rate (line-of-sight), and capacity (throughput) that are discussed in further detail in this chapter.

The literature answers question 4 by recommending the coexistence of different generations of V2X to overcome the shortcomings discussed in question 2, and meet the requirements discussed in question 3.

In conclusion, the literature suggests that the integration of state-of-the-art V2X technologies (and those to come) lays a solid ground for the real-world implementation of the theories and algorithms that we will develop in WP2.

4 Data collection and state-estimation for cooperative control

WP2 deals with incentivising cooperative systems: drivers pay - or are paid – to improve their travel time – or the travel time of other traffic participants. Collecting and exchanging data, filtering these data, and using these data to realise optimal cooperative control in a secure manner, are pivotal tasks.

In the spirit of the DIT4TraM project, decentralisation is a key concept here. This means that for our control approaches. That does not per say imply that the information only pertains to local conditions: *cooperative vision* (or *perception*) is one of the important concepts in cooperative systems. Here, we will explore the state-of-the-art regarding this concept.

Next to – generally microscopic – data on the current – and possibly future – traffic state, data on the value of time, personal values, etc., on the individual traffic participants will be required. Ways to collect these data will be discussed as well.

In sum, this chapter deals with sensing for cooperative systems. It looks at the type of sensors that are used, which data are available, what is the role data processing, estimation, which messages are to be exchanged between vehicles, etc.

The chapter starts with a short description of the survey approach for this topic. Next, we will summarise the findings along several themes, explained in the next section. We will round up with some implications for WP2.

The main research questions that are considered in this chapter are: which sensor and communication technologies (or combinations thereof) are most suitable for realising (cost-) efficient and secure data collection and communication? Which information is to be exchanged with which vehicles (or road-side systems) at which frequency and aggregation level to achieve the optimal trade-off between information exchange cost and performance of the cooperative vehicle application (e.g., cooperative car-following and lane changing, cooperative intersection control, vehicle routing)? Which methods are suitable for optimally estimating and predicting the state of the system, by combining the different available data sources? How to detect anomalies in the data, either by sensor or communication failure or by a security breach, and how to design robust data collection and communication platforms?

4.1 Search approach and results

We performed our literature scan by using the Scopus database. We used the following keywords combinations to get the first set of results

- Sensors (for) connected (and) cooperative vehicles
- Connected vehicle sensing platforms
- State estimation (for) connected (and) cooperative vehicles

Based on the first selection, we used citation / snowballing techniques and expert judgement to get to the final selection of 27 papers. This by no means provides a complete overview, yet we believe that for the purpose of this literature scan, it provides a solid background into the various topics and issues that pertain to data collection in the cooperative vehicle domain.

In the remainder of the chapter, we will look at the following relevant topics:

- Sensor and communication technology
- Cooperative sensing
- Message (CPM) design
- State estimation and prediction
- Data fusion
- Data security

4.2 Traffic sensor and communication technology

In this first section, we provide a brief overview of different sensor technologies, focussing on cooperative vehicles systems. While not having the objective to be complete, we echo some of the discussions on sensor technologies addressed in our literature scan.

(J. Chen et al. 2019) develop a data processing procedure for the detection and tracking of multi-lane multi-vehicle trajectories using roadside LiDAR. Starting off with a review of different sensor technologies (see Figure 1), they select LiDAR as their main sensing technology for the remainder of their analysis.

Technology	Strengths	Weaknesses
Inductive Loop	• Flexible design to satisfy a large variety of applications. • Mature, well-understood technology. • Large experience base. • Only provides macro traffic parameters (e.g., volume, presence, occupancy, speed, headway, and gap). • Insensitive to inclement weather such as rain, fog, and snow.	• Installation requires pavement cut. • Maintenance requires lane-closure. • Multiple detectors are usually required for monitoring one location; the detection range is short.
Microwave Radar	• Typically, Radar is insensitive to inclement weather at the relatively short ranges encountered in traffic management. • Multiple lane operations are available.	• CW Doppler sensors cannot detect stopped vehicles or stopped pedestrians. • Not cover 360 degrees range.
Video Image Sensor	• Monitors multiple lanes and multiple detection zones/lane. • Easy to add and modify detection zones. • A rich array of data available. • Provides wide-area detection when information gathered at one camera location can be linked to another.	• Installation and maintenance, including periodic lens cleaning; requiring lane closure when the camera is mounted over the roadway. • Performance affected by inclement weather such as fog, rain, and snow; vehicle shadows; occlusion; day-to-night transition; vehicle/road contrast. • Some models are susceptible to camera motion caused by strong winds or vibration of camera mounting structure. • Reliable nighttime signal actuation needs excellent street lighting.
LiDAR	• Able to transmits multiple beams for accurate measurement of vehicle position, speed, and types. • Provide high-resolution data, extremely accurate. • Could cover a large area quickly with 360 degrees view. • Easy to install and maintain. • Work day and night without the influence of light conditions.	• The operation may be affected by colossal rain or snow. • Performance might be affected by fog.

Figure 11 Strengths and weaknesses of mainstream sensor technologies; from (J. Chen et al. 2019).

(Z. Wang, Wu, and Niu 2020) present a state-of-the-art in fusion technology and methods for data from multiple sensors to the benefit of automated driving. In doing so, the authors look at more different sensor technologies, including millimetre wave radar, LiDAR, video, ultrasonic, and GPS, and consider fusion methods to integrate the data stemming from these sensors. Figure 2 shows an overview of the pros and cons of these different technologies.

Type	Advantages	Disadvantages	Max working distance
MMW-Radar	1) Long working distance 2) Available for radial velocity 3) Applicable for all-weather	1) Unapplicable for static objects 2) Generating false alarm easily	5m-200m
Camera	1) Excellent discernibility 2) Available lateral velocity 3) Available for color distribution	1) Heavy calculation burden 2) Light interference 3) Weather susceptible 4) Unavailable for radial velocity	250m (depending on the lens)
LiDAR	1) Wide field of view (FOV) 2) High range resolution 3) High angle resolution	1) Insufferable for bad weather 2) High price	200m
Ultrasonic	1) Inexpensive	1) Low resolution 2) Inapplicable for high speed	2m
DSRC	1) Applicable for high speed(up to 150 km/h) 2) Relatively mature technology 3) Low latency (0.2ms)	1) Low data rate 2) Small coverage	300-1000m
LTE-V2X	1) Long working distance 2) Relatively high data transmission rate(Up to 300Mbps)	1) High latency in long distance(> 1s) 2) Inapplicable for time-critical events	Up to 2km
5G-V2X	1) Ultra-high data transmission rate 2) Low latency(< 80ms) 3) High bandwidth 4) Applicable for high speed (up to 500km/h)	1) Immature application	100m - 300m

Figure 12 Comparison of different sensors; from (Z. Wang, Wu, and Niu 2020).

The authors in (Y. Wang et al. 2022) propose using the sensors in a smartphone to collect data, including lane changing, turning, and acceleration (using the IMU and accelerometers in the smartphone). Using these data, the motion of the ego vehicle is detected and shared with vehicles in the front and in the back. They also research the impact via a driving simulator study. The paper concludes that the results are high-accuracy and can be determined in real-time, given that the phone is placed at a stable position. This provides options for collecting data using retrofitted communication systems.

In cooperative systems, sensing and communication go hand in hand. Therefore, we deem it to be relevant to also discuss some contributions in this domain in the remainder of this section.

In (Szalay et al. 2020), a demonstration of 5G intervehicle communication is described. The system covers information exchange between the vehicles and between the vehicles and the infrastructure. The main aim of the paper is to test the latency of the communication and limitations of the available bandwidth in real-life situations. This is an important issue to address, since the quality of the data available to a vehicle is not only dependent on the quality of the onboard or road-side sensors, but is also affected by e.g., latency in communication.

Finally, (Du et al. 2018) discuss a low latency distributed message delivery platform. The paper describes different experiments showing that the distributed platform can exchange unstructured data with sufficiently small latency, given the norms proposed by the U.S. Department of Transportation. The paper highlights the importance of taking decentralised or distributed approaches to meet latency requirements.

4.3 Cooperative sensing

The concept of *cooperative (or collective) perception* is well accepted to improve upon the individual onboard sensing of vehicles. It describes the fact that in an V2X ecosystem, vehicles may collect and share data *jointly* to increase the amount and quality of the information beyond what an individual vehicle can sense.

Figure 3 illustrates the concept by showing the difference in sensing range (for the ego vehicle), and connectivity range.

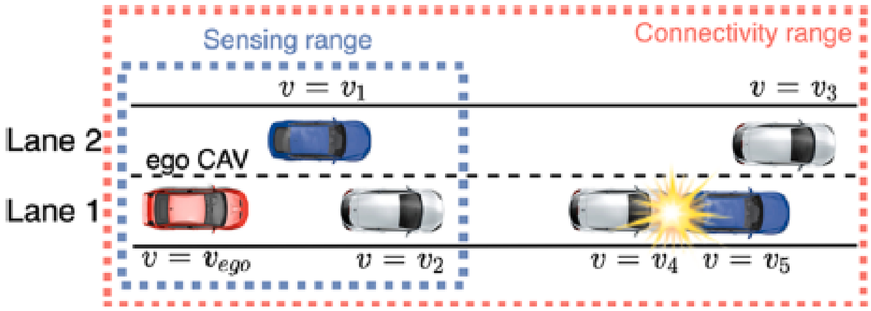

Figure 13 Distinction between sensing and connectivity range, from (Dong et al. 2021)

In cooperative sensing, the data that an individual vehicle collects are augmented with data transmitted by other vehicles. The latter potentially gives rise to additional error due to latency, aggregation of data, etc. From this perspective the communication system is part of the data collection network.

(Dong et al. 2021) discuss the issue of combining short-range (sensor range) and long-range (connectivity range) information for CAVs. This distinction is relevant since different driving decisions require different types of information; see Figure 4. The paper focusses on tactical decisions.

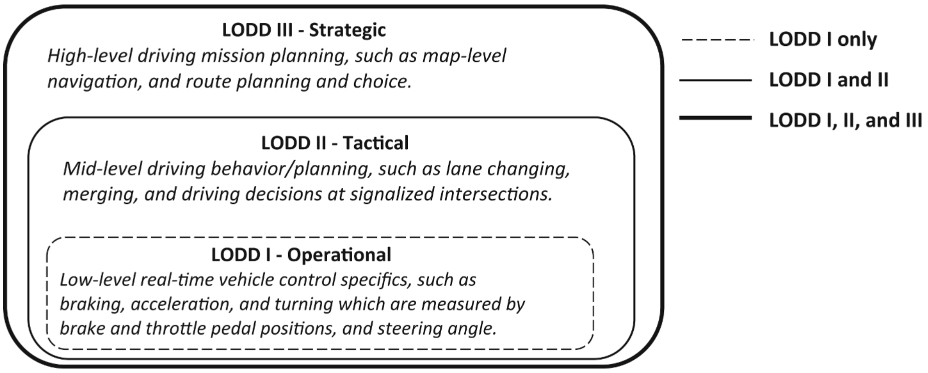

Figure 14 Levels of driving decisions; from (Dong et al. 2021)

The authors of (Godoy et al. 2021) discuss a perception framework that is aimed at merging data (LiDAR and location data) from the vehicle's on-board sensors, and data received from the *Collective Perception System (CPS)*. The authors propose the framework and assess its performance in a realistic setting. The framework considers different stages, as illustrated in Figure 5. They format messages (CPM) that are exchanged about the objects detected and included in the perception framework of the vehicle using data fusion techniques (*Linear Opinion Pools*). The experiments pertain to the detection of roadworks, and a crossroad where occlusion occurs, showing the benefits of the proposed framework.

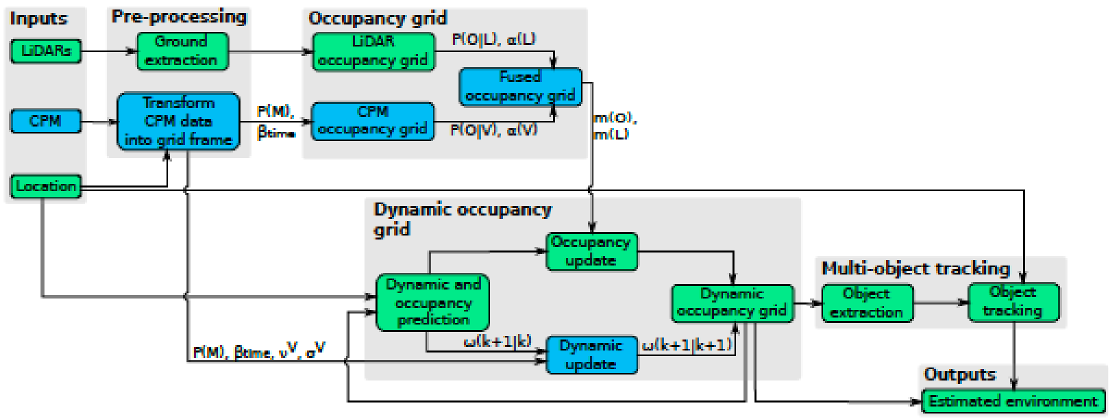

Figure 15 Perception framework scheme (from (Godoy et al. 2021))

(Brambilla et al. 2020) discuss the use of cooperative sensing to improve the performance of Global Navigation Satellite Systems (GNSS). The cooperative vehicles detect a set of passive features in their driving environment, associating them with their on-board observations. They cooperatively share the data to enhance the GNSS information. The authors show via different experiments that their approach enhanced data quality.

4.4 The message design problem

Message (CPM) design deals with the following questions: which sensory data need to be shared and at which resolution? Which vehicles does the information need to be shared with? It goes without saying that tackling this problem is essential in the realm of cooperative sensing, since connected vehicles simply cannot share all the information due to limitations of the communication systems.

In many of the papers considered, the CPM design problem is tackled by looking at the performance of the systems using the messages. This *utility-based approach* is deemed of high relevance many other design problems where sensor network and information exchange design problems are relevant.

In (Abdel-Aziz et al. 2021), a Reinforcement Learning approach is combined with Research Block allocation, and content selection. (Viktorović, Yang, and de Vries 2020) present a *Connected traffic data ontology* (Ctdo), which enables integration of sensor data and geospatial data efficiently, and well as with road infrastructure. Their approach is benchmarked to see the efficiency gain in terms of memory performance and query execution speeds.

(Abdel-Aziz et al. 2020) discuss the issue of information (quality) requirements, i.e., what sensory data is to be shared in the context of cooperative perception. They solve the problem of message content selection by putting forward a Reinforcement Learning selection scheme to learn the message contents maximizing the satisfaction of the vehicles receiving the information.

Also (Aoki, Higuchi, and Altintas 2020) aim to tackle the issue of information selection. Using Deep Learning techniques to let vehicles select which data to transmit to save network resources. The authors present an open-source simulation environment (SUMO) in which the information selection can be tested. Figure 6 illustrates their results in terms of the data reduction using the Deep Learning strategy proposed.

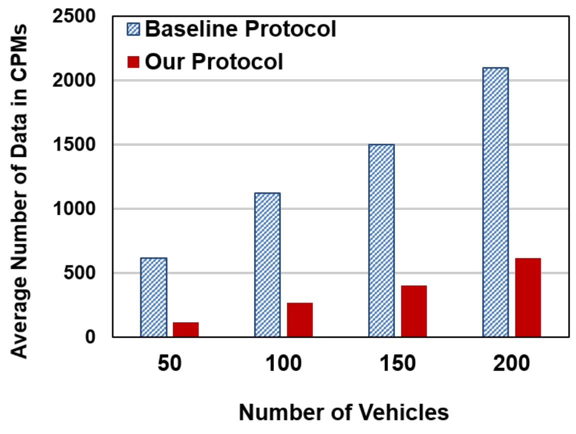

Figure 16 Average number of data shared in cooperative perception; from (Aoki, Higuchi, and Altintas 2020)

Using a Deep Learning approach, (Dong et al. 2021) integrate the information for the local system and the system wide information and to determine the 'information needs' to optimize efficacy of the controller. Next to the data integration, they propose new ACC schemes that use the data to show the impacts. They test their approach using simulation (SUMO).

4.5 State estimation and prediction

This section focusses on state estimation and prediction. In doing so, we distinguish between microscopic and macroscopic state estimation contributions. The information stemming from the former is often used for vehicle control or driving information purposes (e.g., distance keeping, merging). The latter is often more relevant for traffic management purposes or more tactical / strategic driver tasks (e.g., routing, intersection control).

4.5.1 Microscopic estimation and prediction

(Zhu and Ukkusuri 2017) present an approach to estimate the relative positions of connected and non-corrected vehicles using a modified Expectation-Maximisation (EM) Kalman smoother. They illustrate the functioning of their approach using simulation data and via an empirical case (Michigan test bed). The experiments show that the error in the position of the non-equipped vehicles can go up to 5 m; the paper provides suggestions on how this can be improved.

Figure 7 shows the proposed approach by (J. Chen et al. 2019). The authors test their approach using data from different testsides in Reno, Nevada. The LiDAR collects data at 10Hz, while the vehicle speeds are collected for validation purposes using the on-board system. While the authors show that the data quality is good (only qualitatively assessed), they do indicate that weather conditions have a negative impact on performance.

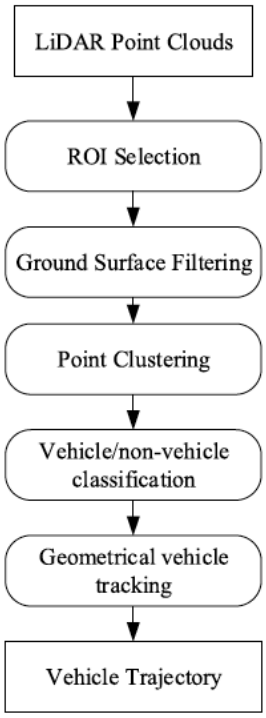

Figure 17 Flow chart of proposed method; from (J. Chen et al. 2019)

In (Bock et al. 2017), road-side sensors are used to determine the trajectories of pedestrians at intersections. These data are subsequently used for the training of Recurrent Neural Networks to predict pedestrian (or bicycle) motion patterns.

4.5.2 Macroscopic estimation and prediction

Macroscopic data is often used for more tactical or strategic purposes, e.g. provision of traffic information and vehicle routing (queue lengths, travel times), traffic control (queue lengths), traffic management (e.g., traffic densities).

(Gao et al. 2019) illustrate the use on-board sensors and C2X for queue length estimation using a combination of artificial neural networks and shockwave theory. While the authors only use position data, they show the performance of their approach using synthetic data even in case of low penetration (Vissim), if there is at least one connected vehicle per cycle [state estimation].

In (Aljamal, Abdelghaffar, and Rakha 2020), traffic density is estimated using connected vehicle data using different types of linear and nonlinear filters (i.e., (adaptive) Kalman and Particle filters). The authors use travel-time measurements for cooperative vehicles. Their main conclusion is that the linear Kalman filter outperforms the other filters, due to its accuracy and simplicity.

(Bekiaris-Liberis, Roncoli, and Papageorgiou 2017) discus the use of position (including lateral) and speed information of connected vehicles in combination with road-side detector systems (e.g., inductive loops). They consider the sensor network problem (number and location of roadside sensors) from the perspective of state observability. Using the NGSIM data set, the performance of the proposed method is assessed.

(Emami, Sarvi, and Bagloee 2021) focus on the estimation of network-wide traffic states for MPC strategies. Using a combination of Kalman filter and Neural Network approaches for estimation and prediction of the network-wide traffic state, the paper aims to estimate the situation for equipped and non-equipped vehicles. The paper illustrates how the state-estimation relates to the performance of the signal control strategy for different penetration rates.

(Y. Wang et al. 2022) present real-time data fusion method where both the traffic state (TSE problem) and the parameters of the prediction model (OMPE problem) are jointly estimated. The paper presents a broad overview of data fusion methods, including different formulations of the state model (Eulerian and Lagrangian formulations), different type of filtering and fusion approaches, as well as different types of data. The authors use NGSIM data to show the extent in which the quality of the results depend on the quality and semantics of the collected data, discussing the relative importance of OMPE.

4.6 Data fusion

Data fusion entails the combination of different – potentially also semantically different – data sources to improve the estimate of the system state or the inferences based on the multi-source information available.

In the context of cooperative systems, (Z. Wang, Wu, and Niu 2020) present five different fusion strategies, classified according to:

1. Fusion strategies based on discernible units
2. Fusion strategies based on complementary features
3. Fusion strategies based on target attributes
4. Fusion strategies based on multi-source decisions
5. Analyses based on results

These strategies are essentially reflecting the level at which the information is fused (e.g., at the level of the raw data, at the level of information stemming from the data, or at the level of the decisions made based on the data).

The authors conclude by providing several recommendations on future research directions in the domain of data collection with and for connected vehicles. These recommendations roughly pertain to security issues, multi-target tracking, application of deep learning methods, and fusion multi-semantic data.

(X. Chen, Ji, and Wang 2020) discuss the fusion of data from onboard sensors with data received from other systems via inter-vehicle communication services. The authors focus on improving self-localization accuracy using Bayesian inference. Figure 8 shows a schematic of the approach presented.

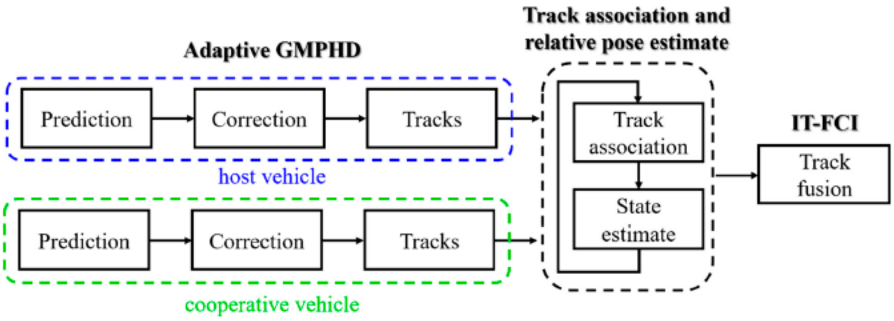

Figure 18 Proposed cooperative multi-vehicle tracking framework; from (X. Chen, Ji, and Wang 2020)

The authors present the results of their approach for a case of seven target and two intelligent vehicles, showing that the fusion increases accuracy of the target vehicle data collection.

(Kuutti et al. 2018) provides an overview of different localisation techniques and compares and assesses them for autonomous vehicle applications. They argue that while in theory data accuracy can be achieved that is sufficient for autonomous driving, the cost and reliability (in certain traffic situations) need to be considered. Combining on board information with off-board information and information from other vehicles can yield important improvements in quality at lower cost. In the latter case, penetration rate will play a crucial role.

(Xiao et al. 2019) present a unified theoretical framework for multiple-target position by fusing heterogeneous data from multiple sources (on-board sensors and V2X technology). Via theoretical and numerical studies, the authors show that in combining data from global navigation satellite systems, INS and HD maps with data from the onboard sensors, provides information of sufficient accuracy for high-level automated vehicles. The nonlinear optimisation problem is solved using the Levenberg-Marquardt method and tested using Vissim.

4.7 Data security

One important issue is data security: while data can be used to enhance improve efficiency and safety of driving and travel operations, malicious data potentially can have massive impact on traffic safety.

Several research address this topic in the context of cooperative systems. (Ta and Dvir 2020) focusses on security issues for data and information exchange of cooperative systems. They propose a secure high-level system architecture and protocols, validated using simulation.

(S. Liu et al. 2019) explores the applicability of edge computing for autonomous vehicles. They highlight the importance of sufficient low-power computation systems, and the importance of data security to ensure traffic safety. After assessing the state of the art, the authors explore different solution approaches to address the main challenges.

(Al-Turjman and Lemayian 2020) discuss security in Vehicle Senor Networks. They provide an overview of the current state-of-the-art. The authors discuss current communication technologies and their security concerns.

(X. Song et al. 2020) consider the issue of state estimation from a security perspective., i.e. in case of a false data injection attack. They present a novel approach that reconstructs the motion of vehicles using the principle of compressed sensing to reconstruct the state of the vehicles. [security]

Somewhat beyond the topic of security only, (Biron, Dey, and Pisu 2016) discuss an approach to determine faulty data either due to communication failure or due to faulty sensors in the context of CACC. They show the performance of their scheme via several simulation studies.

4.8 Conclusions and possible research directions for WP2

In this chapter, data collection, state estimation and prediction for cooperative systems was discussed. Based on the review of 26 papers, we can conclude that the amount of research on this topic is sharply increasing. The main questions that are addressed in these papers are:

1. Which sensor and communication technologies (or combinations thereof) are most suitable for realising (cost-) efficient and secure data collection and communication?
2. Which information is to be exchanged with which vehicles (or road-side systems) at which frequency and aggregation level to achieve the <u>optimal trade-off between information exchange cost and performance</u> of the cooperative vehicle application (e.g., cooperative car-following and lane changing, cooperative intersection control, vehicle routing)?
3. Which methods are suitable for optimally estimating and predicting the state of the system, by combining the different available data sources?
4. How to detect anomalies in the data, either by sensor or communication failure or by a security breach, and how to design robust data collection and communication platforms?

With respect to question 1, many papers suggest that a combination of different sensing techniques, onboard and roadside, provide the most promising opportunities to determine information for different cooperative applications cost, efficiently.

Regarding question 2, different papers take an approach where discerning which data is to be exchanged is determined by the (expected increase in) performance of the application that uses these data. This bears strong relevance for the information exchange protocols for the system to be developed in WP2. In the considered literature, often reinforcement learning approaches are used to tackle this design problem.

Another decision that is relevant for the approach design of WP2 is choosing the method to clean and combine the data (question 3). The considered literature either relies on classical traffic flow theory modelling in combination with filtering techniques or uses data-driven approaches.

Question 4 relates to the issue of security, which becomes of considerable importance in 'beyond-pilot' applications.

5 Control methods for cooperative traffic management at local bottlenecks

In this chapter we discuss the approaches for traffic control at local bottlenecks. Most existing traffic controllers operate on the macroscopic level and aim to improve or maximize the overall system's traffic performance. However, optimizing for the overall performance doesn't necessarily imply that all participants benefit equally. It doesn't even imply that all participants benefit, and both may be considered unfair. In addition, different user classes, modalities, or individual traffic participants may have different interests, e.g., different values of time, and optimizing under the assumption that everybody's interest (value of time) is equal, will not only lead to a sub-optimal result, but may also increase the unfairness of the system. WP2 aims to develop incentive-based control approaches, that use incentives (charges or payments) to ensure system-optimal behavior (as a collective of the individual interests), and to ensure fairness. Besides the objectives of the traffic participants, the road manager may also have a policy to prioritize certain travel modes or user classes. The approach developed in WP2 should be able to express such preferences.

In some forms of incentive-based traffic management the vehicles will receive individual driving instructions, but the execution of the instructions will depend on the driver's willingness to comply. For roadside systems, where compliance is an issue, there exist technologies for the enforcement of the traffic control signals, such as red light running or speed cameras. However, in the case of individualized instructions, the enforcement should be also realized on the individual (vehicle) level. Also (Rios-Torres and Malikopoulos 2017b) lists it as one of the challenges in the transition from mainly human-driven vehicles to CAV-based traffic management, to incentivize system-optimal solutions to human drivers in mixed traffic. Therefore, we will include a discussion on compliance and enforcement.

The focus of this chapter is on local bottlenecks where the traffic management measures imply a trade-off between different users, user classes, or modalities. The most typical bottlenecks of this type are freeway on-ramp merges and weaving areas, and signalized intersections.

Since the envisioned technological setting of WP2 is a mix of roadside systems and different levels of connected and automated vehicles (CAVs), we discuss both, roadside (macroscopic) and CAV-based traffic control systems.

So, the main questions that will be answered, are: What are the main relevant characteristics of the control approaches for local bottlenecks and how do they relate to incentive-based traffic management? What are the main traffic mechanisms that are exploited for control? What are the typical control objectives? Is policy and fairness considered, and if it is, how? What are the typical mathematical techniques? Is (non-)compliance considered, and if it is, how?

To address these questions, in the remainder of this chapter we will discuss for freeway on-ramp merges and weaving areas, and for signalized intersections the traffic mechanisms that are relevant for the traffic performance of these bottlenecks, and how traffic control measures can exploit those mechanisms to improve performance. Typical formulations of the traffic control problem in terms of objective and mathematical control approaches will also be discussed. Also, relations to policy, fairness, compliance and enforcement are discussed.

5.1 Mathematical control approaches

In this section we discuss the mathematical formulation of the control approaches on a conceptual level. In the field of systems and control, and even in the field of traffic control, there exists a wide range of control approaches. Here we discuss only the most important ones that occur in the cited literature.

The typical control objectives on the macroscopic traffic flow level are traffic performance related (such as total travel time, throughput), total emissions, total fuel (or energy) consumption. On the microscopic level, often the same quantities are used as control objectives, but formulated per individual vehicle. In addition, other aspects, such as acceleration, jerk (time derivative of the acceleration), vehicle safety (distances to other vehicles) may be included. (N. Chen et al. 2021; J. Liu, Zhao, and Xu 2021).

Control approaches can be classified into *feedback* or *feedforward* methods. While feedback methods always measure the output of the controlled process and use that information to determine the appropriate control actions, feedforward methods only use other, external influences (the so-called disturbances) that influence the behavior of the process. Since feedforward methods determine the control action only based on the measurement of the disturbances, there is no way to observe whether the control actions have led to the desired result, and thus there is no way to correct the control actions if the outcome is not as desired. Feedback methods do measure the output and can therefore correct for deviations caused by disturbances, modeling errors, sub-optimal control actions, etc. Another important difference is that if the controller is stable and the controlled process is stable, then a feedforward structure will also be stable, but in a feedback structure an unstable process can be stabilized by a proper controller (under some conditions), but a stable process can also be destabilized by a poorly designed feedback controller. That means that care must be taken in the controller design. The ability to stabilize unstable processes is particularly important for traffic systems because they tend to be unstable when operating at capacity. Most of the traffic control systems are of the feedback type due to their better correction ability, and their possibility to stabilize traffic.

Model-based predictive control (MPC) is a feedback control method that uses a prediction model embedded in the controller. This model predicts the (macroscopic) future evolution of traffic or the (microscopic) vehicle trajectory, based on the current state of the traffic or the vehicle and based on the plan for the control signals. Using this prediction, the plan for the control signal is chosen such that it minimizes (or maximizes) a certain pre-defined objective function (expressing the resulting travel time, fuel consumption, etc.). When the optimal control signal is found, it is applied the real process. When new state measurements arrive, a new prediction-optimization step is performed, with the prediction horizon shifted one step towards the future.

In general, the fact that the controller uses predictions is relevant for processes where there is a time delay between the control actions and the resulting effect and the performance of the system. In traffic such delays often occur, because resolving a jam or a queue takes time, or because the arrival time of a vehicle at a certain point is also determined by the speeds in the past. For these reasons, it is often necessary to optimize traffic control actions with a sufficiently long prediction horizon.

In an MPC-based controller an optimization problem is solved every time that new measurements are available. The solution method depends on the type of the optimization problem, and include Pontryagin's minimum principle, sequential quadratic programming, linear programming, mixed-integer linear programming, multi-level optimization, branch-and-bound, and many others.

MPC is a flexible control method, because the objective function and the prediction model can be easily replaced. This makes it very suitable for incentive-based control, where the overall control objective depends on the collective of the individual objectives and may also depend on the policy of the road manager.

The possible drawback of the method is the relatively high computation time that is needed for finding the optimal control signals. Also, the fact that the method relies on a prediction model, makes the controller performance sensitive to the prediction accuracy. However, in many cases the feedback nature can compensate for the prediction inaccuracies.

Learning-based approaches are gaining popularity due to some promising properties compared to conventional methods, such as the ability to operate well with complex nonlinear processes (and avoid a possible model mismatch as inherent to model-based methods), to handle high-dimensional data. Most typically, (deep) neural networks or (deep) reinforcement learning (J. Liu, Zhao, and Xu 2021; H. Wang et al. 2021) approaches are used. However, learning-based approaches need training, where the controller explores the possible control actions, and learns from the outcomes. This implies that also less favorable control actions are taken. While in simulation this is acceptable, in practice it is questionable whether poor performance for the sake of learning would be acceptable. An advantage of learning methods compared to optimization methods is that once learning is completed, the learning-based controller doesn't need recalculation (optimization) of the control signals, so their computational demands in the application phase is much lower, and it is easier to operate them in real time.

Heuristic / Domain-based control methods are focused on the properties of the processes that they will control. The control design is adapted to, or exploits, the properties of the process that will be controlled. An example is the classical traffic signal control design, where the design is focused around finding the right combination of green phases, and the timing that respects the clearance time of conflict areas, etc. Since domain-based methods are tailored towards specific processes, they can be powerful, but also hard to transfer to other domains or to other objective functions. The lack of flexibility regarding the objective function, makes these approaches less suitable for cases where the exact objective dynamically depends on the specific vehicles (and drivers) who are at the bottleneck, such as in some forms of incentive-based control will be the case.

5.2 Control approaches for various bottleneck types

5.2.1 Freeway on-ramp merges and weaving areas

Mechanisms

The merging task of drivers that merge into the freeway from an on-ramp is among one of the most difficult driving tasks, because the driver has to simultaneously synchronize its position with a gap in the mainline traffic and synchronize its speed with the mainline traffic. In addition, the length of the merge area is limited, and drivers will often force themselves into gaps that lead to headway distances in front and behind them that are shorter than what drivers normally would accept.

The merging process can lead to a traffic breakdown and a jam, when the traffic demand on the mainline and on-ramp exceed the capacity of the freeway ramp section, but also when temporary disturbances occur, such as "forced" merging, or temporary peaks in the main line or on-ramp traffic. Temporary peaks in mainline traffic can be caused by vehicles travelling at free-flow speed but very close to each other, and on the on-ramp by an upstream traffic signal that releases vehicles in platoons toward the on-ramp.

Once a breakdown occurred, the capacity of the on-ramp section will be significantly lower than what it was in free-flow, which is called the *capacity drop*. This capacity drop may prevent the return of the traffic state to the free-flow state, even if the disturbance was only temporary and the overall demand did not exceed the available capacity, because after the capacity drop the capacity may not be enough anymore to server the total demand.

Another adverse effect of jams at on-ramps is that the jam on the mainline may propagate to an upstream off-ramp, where it will block even the traffic that wants to leave the freeway.

The conventional approach to prevent a breakdown in the ramp section or to recover from a jam to free flow, is ramp metering. In ramp metering a traffic light on the on-ramp limits to flow that enters the freeway, which can prevent a breakdown or eliminate the jam in the on-ramp section. Ramp metering often also distributes the arrivals of the vehicles from the on-ramp more evenly.

Systems involving CAVS in ramp merging, exploit the facts that CAVS can drive in a safe and stable way with smaller headways (and therefore can accept smaller gaps), can respond faster than manual vehicles, and can be instructed to create gaps at (more or less) the right locations in the main line (Rios-Torres and Malikopoulos 2017b).

Control approaches

In (Papageorgiou and Kotsialos 2002) the classical and most frequently used macroscopic ramp metering approaches are discussed, such as the feedforward demand-capacity method, and the linear state-feedback ALINEA method. In general, the main purpose of such systems is the improvement of traffic flow-related performance measures, such as (system) travel time, delay, and average throughput**.**

Ramp metering is unfair by its asymmetric nature. If ramp metering can prevent a breakdown, the traffic on the freeway always will have a shorter travel time, while the traffic on the on-ramp may have a shorter or longer travel time, depending on the situation, but even if the traffic on the on-ramp has a travel time reduction, the reduction is always less than the reduction of travel time of the mainline traffic. A more fair approach could be to hold back traffic on both, mainline and on-ramp, such as in (Carlson, Papamichail, and Papageorgiou 2011), where besides ramp metering, variable speed limits are used to flow to the bottleneck from the mainline. While in (Carlson, Papamichail, and Papageorgiou 2011) fairness is not explicitly considered, in (Iordanidou et al. 2016) a delay balancing approach is proposed for the coordination of various control measures, such as ramp metering and variable speed limits.

The approach in (Scarinci, Heydecker, and Hegyi 2013) uses a mixed CAV-macroscopic method, in which gaps are created on the mainline by slowing down CAVs at the right moments, and using conventional ramp metering to fill the gaps with platoons of vehicles from the on-ramp.

CAV-based RM In general, the objectives are the improvement of travel time, improvement of safety, reduction of fuel consumption and emissions (Rios-Torres and Malikopoulos 2017b). The CAV-based on-ramp merge approaches are more focused on the proper matching of the mainline gaps and the merging vehicles, and the trajectories of the vehicles while approaching the merge. In most approaches the overall merge problem is decomposed into a merge sequence determination problem (in what order the vehicles from the mainline and on-ramp should follow each other), and a trajectory control problem (how the vehicles arrive at the right moment at the right spot).

The determination of the merging sequence can be rule-based or optimization-based (N. Chen et al. 2021). The rule-based approaches determine a reasonable merging order based on heuristics, or for example, based on the predicted arrival times at the merge location, or based on a first in, first out rule, defined for a zone that includes road stretches on both main line and on-ramp, upstream of the merging zone (Rios-Torres and Malikopoulos 2017a). The optimization-based methods find the best merging order in some or all the possible orders, according to some performance measure, such as the overall delay. The approaches in (Jing et al. 2019; Min et al. 2021) combine game theory for merge sequence optimizaton with optimal control for trajectory optimization.

There are also approaches that integrate the optimization of the merge sequence, and the vehicle trajectories. For example, in (Zhao, Liu, and Ngoduy 2021) a bi-level or hierarchical [5] control approach is used for autonomous intersection control, where in the upper level the crossing sequence, and on the lower level the vehicle trajectories is optimized.

It is remarkable that the conventional and the CAV-based approaches focus on totally different mechanisms. The CAV-based literature doesn't even mention capacity drop or off-ramp queue spillback. However, for mixed traffic, where a fraction of the vehicles is human driven, it can be expected that the capacity drop may still play a role, and the risk of off-ramp spillback will not disappear by the transition to CAVs.

A detailed and extensive overview of control concepts of ramp merging with intelligent vehicles with different levels of automation can be found in (Scarinci and Heydecker 2014).

In freeway weaving areas the high concentration of lane-changing vehicles reduces the capacity of the weaving area, and that may lead to a traffic breakdown. The main approaches are methods that aim to distribute the lane changes across the available weaving area, methods that manage the input volumes to the weaving area, or CAV-based methods where the advantages of autonomous driving are exploited (Bai et al. 2019).

While these methods determine merging sequences, and therefore "exchange" delays of individual vehicles (compared to other merging sequences), none of the methods considers fairness, or the trade-off of individualized costs in the approaches.

Regarding compliance and enforcement, conventional ramp metering systems in practice usually have some form of enforcement, such as red-light running camera's or smaller a downstream facing red light that helps the police to identify the vehicles that run through red. One of the reasons why enforcement is necessary is that in a case of a successfully operating ramp metering system, there will be no jam on the freeway, and a driver on the on-ramp might conclude that the ramp metering system is active unnecessarily. Furthermore, ignoring the red light, is not particularly unsafe (so drivers might be more tempted to do so), but more necessary for traffic performance reasons. The theoretical approaches don't mention compliance issues. In the case of CAVs, it is often implicitly assumed that the vehicle will exactly follow the calculated instructions. However, this might be different for connected but human-driven vehicles, or for CAVs where the driver can take over the control.

5.2.2 Signalized intersections

Mechanism

Signalized intersection control has been a subject for research for several decades. A wide range of approaches have been developed, ranging from fixed-time control, vehicle-actuated control, green wave coordination, to coordinated networks. The most typical techniques used are either domain-based analysis (i.e., traffic flow theoretic) or optimization-based, using prediction models that relate the signal timings to the expected performance and search for the timing that leads to optimal performance. More recently, also learning-based approaches are gaining attention.

The conventional way of operation of traffic signals is that certain movements (a specific combination of from- and a to- direction) get green for several seconds, during which a *platoon* of vehicles can cross the stop line. Safety is ensured by only allowing green at the same time for different movements, if they are non-conflicting (though, a few exceptions exist).

The main mechanisms that are considered to affect the control performance, are:

- *The occurrence of unused green time***.** If no vehicles are crossing the stop line during green, then that may mean that green could have been shortened without losses for the considered movement, and other conflicting movement could have been given green earlier, which would have reduced the delay.

- *The combination of non-conflicting movements in phases so that they can get green at the same time.* Non-conflicting movements can be combined in a phase, so that they get green at the same time. The optimal combination depends in general on the traffic demands of the different movements. In some countries it is common to pre-define the combinations (as in the ring-barrier structure, that is common in North America), but in many other countries the structure can be defined offline (by design) or online (by controller).

- *The order of phases.* Even if the phases are fixed, they may follow each other in different order. Different orders may lead to different performance, because of the clearance time between different conflicting movements may be different. Often the order of the phases is pre-defined (by design) but approaches that change to phase order online (by controller) are gaining popularity.

The vast majority of the approaches that consider connected or automated vehicles for intersection control, assume 100% penetration of fully connected and automated vehicles. These approaches typically focus on the conflict areas at the intersection, i.e., the physical area that is used by two conflicting movements, and formulate approaches for safe and efficient use of the conflict areas.

The main sources of travel time improvement (compared to conventional traffic signals), as also mentioned in (Zhao, Liu, and Ngoduy 2021), are the following:

- The fact that in low-demand cases the vehicles don’t have to wait for their turn in the signal control cycle, but can cross the intersection safely if there is a sufficient gap between the other crossing vehicles from conflicting directions.

- Conventionally, the yellow times and clearance times are chosen to be on the safe side given a distribution of possible vehicle behaviors. However, for VACs yellow time is considered unnecessary, and the clearance time can be much shorter, due to the better controllability and predictability of VACs.

- The car-following gaps for vehicles on the same movement, and the acceptable gaps for conflicting movements are typically smaller than for human driving.

- In many CAV-based approaches the trajectory of the vehicles approaching the intersection is optimized.

Control approaches

Safety is ensured by making sure that a conflict area is only used by vehicles of the same movement (Zhao, Liu, and Ngoduy 2021), or by properly scheduling platoons of vehicles of the different movements (Xie et al. 2012). Instead of scheduling, there are also reservation-based systems, where reservation requests from the vehicles are confirmed or rejected by the signal controller (Dresner and Stone 2004; 2008). There are also methods that consider the whole vehicle trajectories and try to minimize the overlapping trajectories of vehicles from conflicting movements and use constraints to ensure safety. However, according to (Zhao, Liu, and Ngoduy 2021) for this type of approach it is hard to find feasible solutions due to the complexity and the number of constraints, and the proposed solution will often fall back to a rule-based solution.

From performance perspective, the control problem is often decomposed into a passing sequence determination and the optimization of the vehicle trajectories. This is like the approaches for on-ramp merging. This similarity is also emphasized in (Rios-Torres and Malikopoulos 2017b) and it is suggested that the approaches for on-ramp merging can be easily transferred to intersection control or vice versa. However, there are also some differences. In signalized intersection control, one vehicle often crosses more than one conflict area, and therefore the crossing sequence and the trajectory optimization cannot be solved separately. Also, the conflict area between two movements in intersection control is fixed and relatively small, while in freeway weaving or on-ramp merging, the location of the lane change and merge can vary over a much larger area. Furthermore, when human drivers are involved in freeway merge and weave control, the capacity drop may still occur, and should be considered.

There are also approaches that combine automated vehicle trajectory control with conventional traffic signal control, implying a platoon-oriented crossing of the different vehicle streams. For example, in (M. Liu et al. 2022) a method for the joint optimization (single layer) of signal control and automated vehicle trajectories is presented.

In practice there may be also a difference between on-ramp merge control and intersection control in formulated policies. For ramp metering often a constraint on the ramp queue lengths is formulated, to prevent spillback to upstream intersections. For signalized intersections a wider variety of policies are common, such as conditional or unconditional priority of public transportation, minimum green time and maximum cycle time for low-demand side directions (to prevent excessive waiting times), priority for cyclists (e.g., the possibility for a second realization of green during one signal control cycle), and absolute priority for emergency vehicles. In most practical systems, such priorities are decided by logical or heuristic rules, typically no trade-off is made between the costs of the different control options.

More recently, the focus in scientific literature is shifting toward mixed traffic. It is more and more realized that to make the transition from fully manual to fully CAVs possible, there is a need for control methods that can benefit from any penetration rate of CAVs.

In (K. Yang, Guler, and Menendez 2016) an intersection control approach and vehicle trajectory design is presented for mixed traffic where three classes are distinguished (conventional vehicles, connected but not automated, connected and automated), and the control performance is optimized for the connected vehicles, and the control actions are the trajectories of the automated vehicles. Another intersection control approach for mixed CAVs and conventional vehicles, formulates the control problem as a resource scheduling problem (Li and Zhou 2017). In (He, Head, and Ding 2014) a signal control (and coordination) approach is developed where priority eligible vehicles, such as emergency vehicles, transit buses, commercial trucks, and pedestrians can send requests for priority. The signal timing is then optimized for a weighted sum of delays of priority vehicles and the other vehicles (and a term to reward coordination). In (Guo and Ma 2021) a learning control approach is developed, based on neural networks and reinforcement learning, for the optimization of signal control and CAV trajectories in mixed traffic.

One of the fundamental questions in mixed manual and automated traffic is whether the two vehicle types should be in one stream or should be separated. In (David Rey and Levin 2019) an intersection control approach is developed, with dedicated lanes for autonomous vehicles with separate signals, called blue phases, combined with the conventional green-yellow-red signals for the manual vehicles.

In (David Rey, Levin, and Dixit 2021) the theory of auction mechanism design is used to develop an incentive-based approach for intersection control. The payments and priorities are determined based on user-declared value-of-time and maximize the social welfare (in the sense of total of costs of travel times and payments). To the author's best knowledge, this is currently the only approach where individual user preferences are considered, and incentives are used to balance the costs and benefits of the system-optimal control solution.

5.3 Compliance and enforcement

In real-world, for conventional roadside traffic control systems, enforcement is typically motivated by safety or traffic performance reasons. In the case of traffic signals both safety and traffic performance play a role, in the case of conventional on-ramp metering the primary reason is traffic performance. The violation of a red ramp metering signal may not be particularly unsafe (as it is similar to not having ramp metering), but it will adversely affect the traffic performance. In practice compliance is achieved by fines in the case of non-compliance, and the fines are high enough to practically convince all drivers to comply with the traffic signals.

In the literature on controller design for traffic management, compliance is not considered explicitly. For roadside systems it is usually implicitly assumed that there is enough enforcement available (e.g., red light camera's) to make traffic behave according to the control signals, and for CAVs it is implicitly assumed that the CAVs will exactly execute the requested behavior (trajectories, etc.) since they are automated. However, for incentive-based control, drivers or vehicles may intentionally or unintentionally deviate from the requested behavior. A driver may simply decide to not follow the requested solution, or there may be technical reasons why a vehicle is not able to exactly follow the requested solution (e.g., a vehicle merges in a wrong slot, because the vehicle couldn't accelerate enough, or because the slot was not where it was predicted to be).

Also, the fairness of a control solution may affect compliance. Many of the traffic controllers affect the order in which vehicles pass the bottleneck. In some cases, the order is a consequence of the nature of the bottleneck or the controller. For example, ramp metering holds back the vehicles on the on-ramp, or intersection throughput can be maximized if movements that carry more traffic get more green time (e.g., movements with more lanes). In other cases, the controller is explicitly formulated according to some policy that prioritizes a certain vehicles or vehicle class (e.g., cyclists, public transportation, trucks). So, the system optimal control action may be unfair to certain drivers, and drivers may be less motivated to comply with unfair (and form them adverse) control instructions.

In cases of individualized driving instructions, it may be hard to have the conventional roadside enforcement. Compliance will be on vehicle (trajectory) level, and non-compliance might be unintentional, and gradual. Instead of conventional enforcement, payments or charges could be imposed depending on how the realized behavior affected the cost of the considered vehicle, and the costs of the other traffic. It is a question for future research whether and how incentives could be used to ensure compliance.

5.4 Conclusions

For locall1 bottlenecks, such as freeway on-ramp merges, freeway weaving areas and signalized intersections, a wide range of control approaches exists. Most approaches are either of the conventional type that controls traffic on the macroscopic level, or assuming 100% penetration rate of CAVs. However, the number of publications that address the control problems with mixed traffic is increasing, which is a necessary development to support the transition toward a fully connected and automated traffic system. Currently, the approaches for conventional traffic control tend to emphasize different traffic phenomena than the ones considered for management strategies mainly intended for connected or automated vehicles. The approaches for mixed traffic should combine the two worlds.

In general, the control objectives express a selection or a combination of: overall traffic performance (travel time, throughput), total emissions, total fuel (or energy) consumption. The methods that also optimize the vehicle trajectories, often formulate these quantities at the vehicle level, and include objectives (or constraints) for driver comfort and safety. Approaches that express policy (i.e., trade-off between modalities, vehicle classes, or individual vehicles) or that take individual preferences (value-of-time) into account are rare. A few approaches use weights, logic rules, or self-declared costs to trade-off the interest of the different traffic participants. Including different weighting functions or individual preferences in optimization-based or learning-based formulations is relatively straightforward but understanding the effects on optimal traffic behavior and performance remains largely an open question.

While all the approaches influence the order in which vehicles can pass the bottleneck, fairness is usually not considered. Fairness may become a more important issue in the future, because, first, the vehicle-based control actions widen the range of control options, and therefore may introduce even more unfair solutions. And second, in the case of connected manual vehicles, the driver may not feel motivated to comply if the requested action feels unfair.

In control approaches, optimization-based and the learning-based approaches dominate. Optimization-based approaches have the advantage that the objective function can be easily adapted, the prediction models can be designed to include the relevant dynamics, and control constraints can be naturally included. Learning-based approaches have similar flexibilities, except they don't depend on an internal prediction model, but can learn from the real process. This an advantage, as the control actions can be optimized for the real system, but also a disadvantage, because learning is rather time consuming, and requires considerable exploration, during which the system may perform poorly.

For incentive-based control, the optimization-based approaches seem to be most suitable, mainly due to their explicit handling of the control objectives. In some cases, heuristic, domain-based, or learning approaches might also be used to solve the traffic control problem (even non-optimizing, non-learning approaches), but not in the general case, where the objective function may be dynamically changing.

The cited literature doesn't consider the relation between the traffic control approaches and compliance. However, many control approaches may be unfair, and enforcement for some forms of automated or connected vehicles may be more difficult than conventional enforcement (for example, to enforce merge sequence or exact trajectories). Incentives may provide a way to ensure compliance, but the way how incentives could or should be used, is a question for future research.

6 Incentive schemes in traffic and mobility management

Thus far we have analysed the technical requirements that underlie the objective of WP2, i.e., the development of incentive mechanisms for cooperative connected traffic at local bottlenecks.

Once a suitable technological setup has been identified, ensuring that communication between (a subset of) vehicles and control infrastructure is accurate, timely and complete and appropriate data is collected and processed, control methods can steer the (connected, cooperative) traffic towards a desired state. Determining which state is considered 'desirable' pertains to the given policy objective(s), how these objectives interact, which means for (dis)incentivising are employed, and how effectively are network-wide objectives (e.g., maximising flows & throughput, while ensuring safety and equity, minimising pollutant emissions, …) are translated at the individual bottleneck scale.

This last chapter therefore focuses on the policy aspects of developing decentralized incentive schemes, exploring the available literature in transportation, transport economics, traffic management and control, to answer the following research question:

What are the fundamental objectives of incentive schemes in mobility management, how are optimal values for (dis)incentives determined, and how can this arbitration be carried out through decentralized decision-making?

We organise this chapter as follows: we first discuss which objectives have been historically targeted via (dis)incentive schemes, across the range of strategic, tactical and operational approaches. We then differentiate between approaches employing direct monetary (dis)incentives and approaches relying on other methods to influence road user behaviour. After briefly discussing aspects of user acceptance, fairness and equity in mobility management incentive schemes, we finally draw conclusions on the collected state of the art, and highlight research gaps in relation to decentralization.

6.1 Motivations and objectives of (dis)incentive schemes

In this subsection, we detail a few examples of how (dis)incentive schemes can be used in transportation networks and mobility to attain a variety of objectives, spanning the three levels of planning.

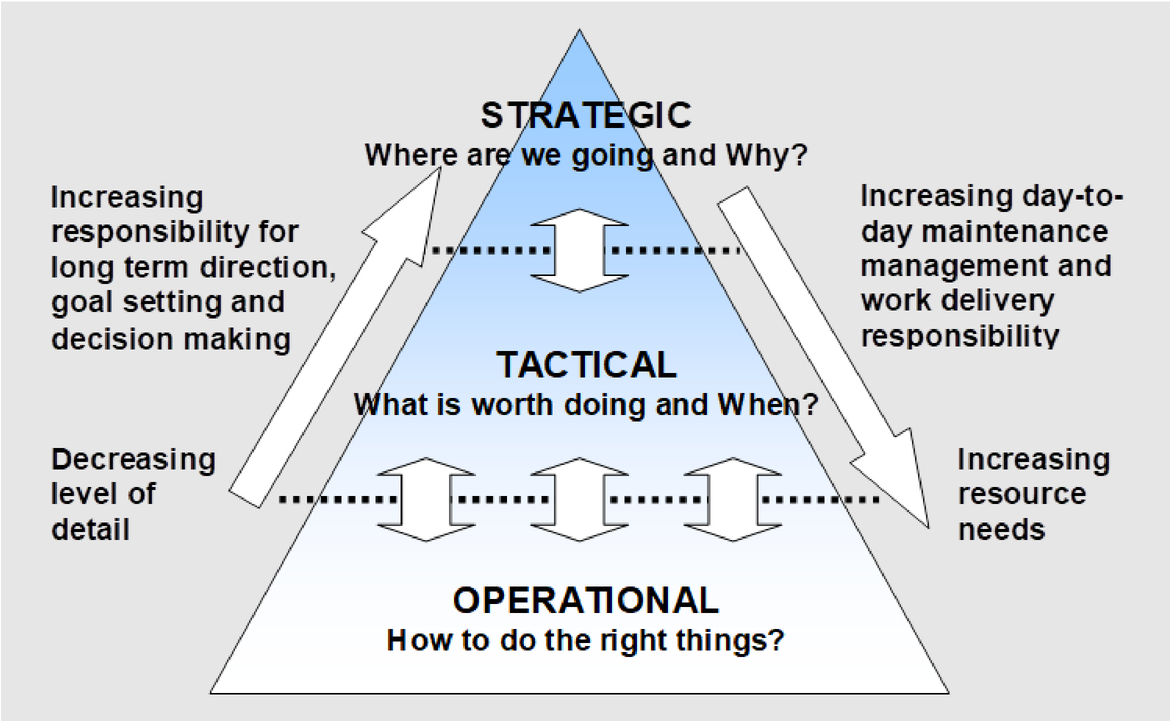

Figure 19: Asset Management pyramid structure (courtesy of the International Road Federation).

Our focus here is in highlighting how sparse and diverse the range of possible objectives achievable by incentive schemes is, without being necessarily exhaustive. In line with our main research question, we briefly comment on the nature of the incentive scheme itself (static/dynamic, unresponsive/responsive) and how central decision-making for the different applications is (centralized/decentralized).

6.1.1 Strategic level

In transportation, strategic decisions typically relate to large scale interventions on a long-term planning scale. These often accompany developments in land use, urbanisation and sprawl, as well as key technical investments e.g. in infrastructure expansion. Examples of long-term strategy can be for example investing in the introduction of new Public Transportation lines, redesigning urban centres to be more inclusive and promoting towards active modes (designating an area as pedestrian only, or low-car), introducing road tax policies aimed at reducing ownership, adding a radial motorway around a major congested metropolitan area to divert traffic away from the city's ring road, etc.

An example of incentive mechanism targeting strategic level decision is the congestion charging system introduced in the mid 2000s in the Swedish capital Stockholm (Eliasson and Mattsson 2006; Eliasson 2009; Eliasson et al. 2009). The scheme was trialled with the explicit objective of impacting long-term decisions on car ownership, PT subscription and perceived quality of living environment in the affected area. The positive trial results have been confirmed as stable trends through long-term evaluation efforts, demonstrating that the incentive mechanism has indeed achieved its strategic objectives.

The congestion charge setting was determined through ample simulation effort, prior to the trialling phase. A limited set of pricing charges was developed depending on the time of day, location, day of the week. Hence, the incentive scheme can be classified as **quasi-dynamic**, while **centralised.** As the pricing values did not however directly depend on the underlying traffic situation, the system was, at least at the time of implementation, **unresponsive**.

Another example of incentive mechanism targeting and/or supporting strategic level decisions is to be found in the work of (Wichiensin, Bell, and Yang 2007). The authors study how congestion charging – i.e. monetary disincentivising of private transportation – can influence a parallel Public Transportation system. This influence is dual: on the one hand, a portion of the road users will be susceptible to mode change, i.e. they will be pushed towards choosing the Public Transportation service, as long as the marginal disutility introduced by this choice (longer waiting times, comfort, added time for walking to/from stops) is counterbalanced by the incentive itself (the marginal utility of taking the car is cancelled by the disincentive).

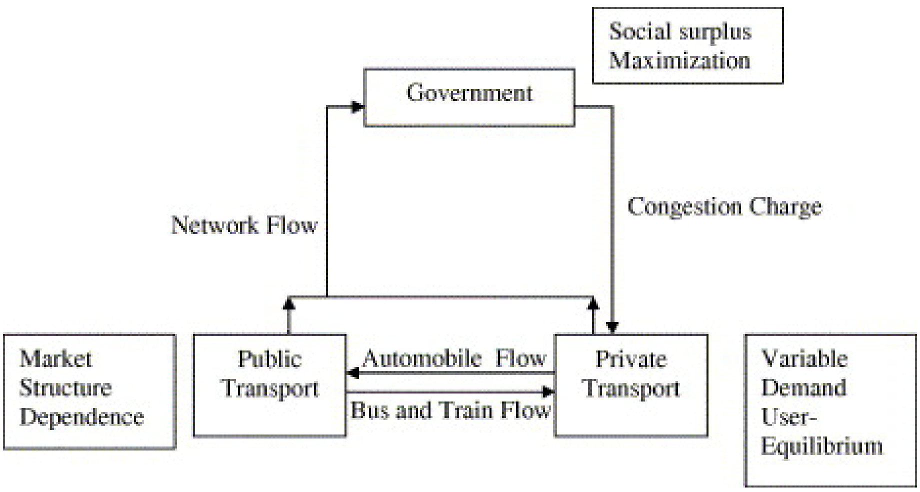

Figure 20: Incentives at Strategic Planning level for increased PT usage / congestion avoidance. Scheme from (Wichiensin, Bell and Yang 2007).

On the other hand, PT operations are not an isolated, independent player in this setting: a clear dependency between road disincentive levels and optimal fare allocation for monopoly and duopoly PT management has been identified. In short, congestion charging might induce an increase in PT ticket fares, as PT operators capitalise on the added demand. This points to one of the main findings of this literature review: explicit consideration of the value chain of all stake holders is paramount in designing a holistic management framework. In this approach, this was achieved by formulating the problem in a fully **centralized** manner. Although explicitly **dynamic** in determining the optimal level of (dis)incentive (i.e. the optimal price), the proposed approach is **unresponsive**, in that it does not rely on measured data to adjust its estimate.

Our literature search failed to identify instances where incentive schemes targeted at strategic planning were accompanied by overt decentralization efforts.

6.1.2 Tactical level

Tactical planning in transportation is most often equated to Transport Demand Management. Rather than targeting longer-term decision-making processes, such as housing, (car, PT subscription) ownership and modal dependence, TDM focuses on mid-term decision-making: influencing within-day decisions such as modal choice along a daily trip chain, activity chain order and, to a lesser degree, composition, route choice, etc.

Typical problems arising at the tactical planning level include, for example, handling repeating, regular demand patterns, such as peak hour traffic, ensuring that the demand is distributed as efficiently as possible onto the limited network supply. Incentive schemes at this level aim mainly at ensuring that a certain Quality of Service is met, e.g. that congestion is kept at a minimum level or that pollutant emissions do not exceed a given threshold.

An example of tactical level (dis)incentive scheme can be found in the work of (W. Liu and Geroliminis 2017). Here the authors assess how **dynamic** pricing of roads and differential pricing of parking spaces influences day-to-day choices for road users. Specifically, users can choose either to drive into the city centre (paying road pricing), drive to the edge of the city centre and then shift to PT service (paying the park-and-ride fee). The authors formulate the problem from the perspective of a single **centralized** entity managing the entire system, and devise a pricing mechanism that successfully maintains the distribution of traffic through the city centre at an acceptable level (minimizes congestion, maximizes throughput, as captured by the Macroscopic Fundamental Diagram), shifting the modal equilibrium into a different point, featuring higher PT adoption. In this instance, parking pricing has been employed in addition to congestion pricing in order to achieve the strategic objective of limiting urban car dependency. The incentive scheme can be considered **responsive**, thanks to its dependency on the measured network accumulation.

A practical trial carried out in the Netherlands in the mid 2000s showed how incentive schemes (as opposed to disincentives, like pricing) can also yield desirable changes at the tactical level. The experiment, detailed in (Ettema, Knockaert, and Verhoef 2010), ran for a duration of three months. Road users were offered a monetary incentive with the explicit objective of reducing peak demand on a motorway leading to the The Hague. The incentive scheme was **quasi-dynamic**, in that the incentive reward was dependent on time and on specific choices (using the peak lane as opposed to not), but stemming from a limited, preordained set of choices (hence not fully dynamic). The given set of choices was entirely **centralized**. The approach ranks as **unresponsive** however, lacking any direct feedback from the network situation.

As with the previous section, we found no approach in literature combining tactical level decisions with explicit decentralization.

6.1.3 Operational level

Finally, operational planning relates to smaller scale within-day dynamics, characterised by short-term choices and actions. Incentive schemes targeting this level are typically designed to support operational management.

An example lies in Autonomous Intersection Controllers. These typically employ auction approaches, collecting the characteristics, desires and requirements of all vehicles approaching the intersection (in the form of declared individual delay costs) and guiding the vehicles through by ranking the bids received. Multiple objectives can be targeted by such approaches, ranging from individual intersection capacity maximisation, to locally measured social welfare maximisation, depending on the associated bidding costs.

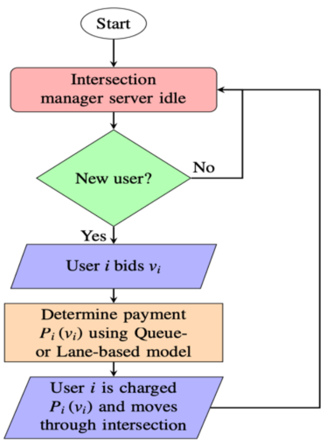

Figure 21: Bidding mechanism (Rey et al., 2021)

In (D. Rey, Levin, and Dixit 2021) the authors develop a dynamic auctioning approach, where the bidding prices that are to be paid (or traded) among vehicles are determined in real-time, based on a stochastic estimation of the different users' expected waiting times. The authors show that the proposed dynamic scheme can be incentive-compatible (i.e., it can lead to social welfare maximisation), under specific assumptions related to the user behaviour at the intersection itself.

Multiple guiding mechanisms can be identified in how to operate an auction-based traffic intersection, ranging from subsidy-based, combinatorial auctioning, marginal cost / transferable utility schemes etc.

These approaches, which are **responsive**, range between **static** and **dynamic** depending on how the auction system determines prices, and are **distributed**, in the sense that the intersections determine their own optimal action with no regard for the remainder of the network, but *not technically decentralized*, in that the objectives of the individual intersection controller might not align or result in desirable network-wide properties.

In conclusion, when focusing on the policy objectives that are targeted by (dis)incentive schemes, we can identify three main trends from literature:

i) Incentive schemes are widely employed across planning levels, featuring diverse objectives in relation to the level of application.
ii) A relationship can be observed between planning level, dynamicity of the proposed schemes and the potential for decentralization.
iii) Decentralization of higher-level objectives is lacking in literature.

In the remainder of this chapter we discuss the differences and knacks of incentive schemes based on direct monetisation, how these compare to approaches based on behavioural intervention, and briefly touch upon issues of user acceptance and fairness. Finally, we draw some concluding remarks.

6.2 Monetary (dis)incentivising

Monetary incentives have long been object of research from transportation scientists and transportation economists. Monetization of interactions carries a direct benefit in terms of user perception: road users have been found to be typically far more responsive to direct pecuniary costs than to other management strategies. In this section we further subdivide the state of the art in three distinct classes: road pricing, where we identify how optimal prices have been determined under different conditions, with the objective of social welfare maximisation; PT pricing and subsidizing, where we highlight the role of the PT operators as additional players with interests other than social welfare maximisation; tradable credit schemes, finally, wherein a non-fiat currency is introduced with a controlled market cap, and necessary to pay the levied prices.

6.2.1 Road pricing

Road pricing has seen ample interest both in research and practice over the course of the last half century. Its objectives are various; levying a road price can help fund the construction of new infrastructure, it can help avoiding excessive traffic towards sensitive areas, such as busy city centres, etc. From a technological standpoint, road pricing is among the earliest adopted strategies, quite commonly through tolling gantries placed in key locations along the transportation network. More recently, higher tech alternatives such as ANPR cameras and connected vehicles have arisen, leading to the possibility of refining road pricing schemes to target specific user groups (or individuals), as opposed to general flows (Clements, Kockelman, and Alexander 2020).

Determining the (dis)incentive value itself, when considering social welfare objectives, has historically been tightly linked with transport economics, leading to mathematical determination of first-best and second-best pricing schemes (Verhoef et al. 1996; Verhoef 2002). From a mathematical perspective, both approaches determine the marginal disutility caused by an individual traveller, and showcase that by internalising the costs associated with this marginal disutility, for each traveller, ensures social welfare objectives.

Current implementations of these classical approaches are however largely **centralized**, **static** and **unresponsive**, as they rely on fixed pricing locations, often on static (or quasi-dynamic) incentive determination, and most often do not adjust the pricing values to the underlying network conditions. Nonetheless, they have been considerably successful in attaining strategic/tactical objectives (Lauridsen 2011).

Recent developments have been focussing on developing advanced pricing strategies, exploiting the availability of real-time information and the technical capacity for fast information exchange (Simoni et al. 2019). This allows for a better capillary distribution of (dis)incentives at the vehicular level, ideally bridging the gap between the refined theoretical conclusions obtained by the traffic economists in the early 2000s and practice. The authors propose two approaches; an approach which is **centralized**, **dynamic**, and **unresponsive**, mimicking marginal cost pricing, and an approach leveraging instead real-time travel time-congestion information, characterised hence as **centralised**, **dynamic**, and **responsive**.

6.2.2 Public Transport pricing & subsidizing

Public Transport pricing features dynamics which are substantially divergent from those of road pricing. This is due to a fundamentally different market setup: other than attempting to achieve user-related objectives (ensuring service, quality, ridership, …), PT systems also must account for the objectives of the operator, whose business strategy creates boundaries and, potentially, pareto optimality between what would be desirable from a social perspective and what is economically viable, if not profitable (Buttazzo, Pratelli, and Stepanov 2006). From a mathematical perspective, this added layer of complexity has called for considerable attention in both modelling the problem of fare planning as well as explicitly accounting for governmental subsidies

(Borndörfer, Karbstein, and Pfetsch 2012). The problems are formulated **centrally**, resulting in complex nonlinear dynamics. **Quasi-dynamic** fares are analysed, with direct consideration of governmental subsidy impacts. Due to the explicit consideration of demand elasticity, the approach can be ascribed to a **quasi-reactive** system, in that the reaction of user choices to changes in the incentive value are partly captured by the explicit elasticity modelling.

Decentralising these dynamics, effectively decoupling (while maintaining representation) the market dynamics of PT operator revenue maximisation from operational concerns arising at the bottleneck level, represents an open challenge.

6.2.3 Tradeable credit schemes

Among (dis)incentive schemes, tradeable credit schemes exhibit considerable flexibility in which objectives they might attain and how effectively they might be implemented in a sufficiently disaggregate manner. TCSs have been recently gaining popularity in research – the underlying principle is simple and promising: rather than relying on fiat currency, a limited amount of credits is carefully introduced in the system and portions of the transportation infrastructure require expenditure of these credits when accessed (H. Yang and Wang 2011). These credits can however be freely traded among individuals, under the so-called cap-and-trade scenario. This implies that, from the point of view of the road authority, the key choices are i) the credit market cap and ii) the credit cost of various infrastructure. After the initial issue of credits, exchange market forces are left with the task of distributing these credits among the road users until a market equilibrium is met. This in a sense represents a *weak decentralisation* of decision-making, in respect to other monetary (dis)incentive policies.

In their work, (Grant-Muller and Xu 2014) have collected numerous literature pointers from the mid 2010s, marking a considerable increase in research interest. In their findings, the authors highlight how while technical feasibility of such a system in resolution of bottlenecks is relatively high, considerable research effort is warranted in developing TCSs capable of achieving network scale mobility management objectives. The network approaches identified by the authors feature **centralised** decision-making, in determining factors such as credit release and costs, featuring however variable levels of **reactiveness** to traffic conditions. Interestingly, some works argue that in the context of user acceptance and political acceptance, **dynamicity** might in fact be a detrimental factor (Dogterom, Ettema, and Dijst 2017).

Monetary (dis)incentives remain a very active area of research and development. Technological advancement has motivated considerable development in how optimal pricing can be determined, across multiple modes, with unprecedented capillarity, i.e., tailored as much as possible to the individual user. While abundant approaches targeting improved responsiveness and dynamicity can be found in literature, aspects related to decentralization of decision-making remain largely unexplored.

6.3 Behavioural (dis)incentivising

While of lesser relevance for the purposes of DIT4TRAM, we believe it worth addressing the (recent) body of literature focussing on developing incentive schemes that do not rely on monetary transactions to achieve management objectives, but rather attempt to influence user behaviour itself. We subdivide this section into two main lines of research: nudging, i.e. approaches that employ pervasive technology to gently steer the behaviour of individuals, and sensibilisation, a conventional approach for influencing popular beliefs and the resulting 'gut' choices.

6.3.1 Nudging

Nudging refers to the practice of influencing the choices of selected individuals through non-coercive means. Rather than imposing a tax or demanding a form of monetary compensation, nudging relies on collecting contextual information, and presenting the user with one of more suggestions, based on said information, that might help them achieve one or more management objectives (Ranchordás 2020).

Unlike monetary (dis)incentive mechanisms, nudging requires user involvement. Users must be informed on what the overall management objective is, as well as how their actions influence it. Choosing whether or not to positively contribute to the management objective – potentially at short-term individual loss – rests entirely with the user. A key requirement for an approach to be classified as 'nudge' is for it to be *easy* and *cheap to avoid*, merely a suggestion, not a mandate.

A classification of different approaches to alter user behaviour can be found in Table 3.

Nudging has received growing interest in the field of transportation, especially in relation to the accompanying technological spread of Internet of Things (IoT) devices. *Digital nudging* allows to deliver personalised contextual information to mobility users, to frame their actions with respect to the wider management goal. This has been shown to be reasonably effective in fostering sustainable transportation objectives (Andersen, Karlsen, and Yu 2018).

Table 4: Behaviour altering strategies, focus on nudging. (Lehner, Mont, and Heiskanen 2016)

Eliminate and restrict choice	**Guide and enable choice**						
	Incentives and information			Nudging			
Laws & regulations	Fiscal incentives	Non-fiscal incentives	Provision of information	Simplification and framing of information	Changes to physical environment	Changes to default policy	Use of social norms

Digital recommender systems for green transportation choices are gaining considerable momentum (Bothos, Apostolou, and Mentzas 2015), with early stage pilots being deployed to assess / predict network-wide benefits ('Code the Streets – Future Digital Mobility Management' 2021). These are indeed an instance of '*simplification and framing of information*' nudging.

Nudging approaches are typically both **dynamic** and **reactive**, as they rely on collection of real-time data in order to deliver relevant recommendations (e.g. a different, more eco-friendly route around the city). Depending on the adopted computational framework, they can be either **decentralised** (e.g., in the case of IoT featuring edge computing) or **centralised**.

6.3.2 Sensibilisation

The establishment of novel social norms and customs can be considered as a form of behavioural (dis)incentivising, tightly associated with nudging (as per Table 3 above).

Sufficient campaigning and widespread information (as opposed to personalized information) can lead to behavioural shifts across the population. Social and psychological forces have been recognised as considerable contributors to choices in mobility – similar in impact to traditionally economic levers and prices (Riggs 2017).

Stated preference surveying (Riggs 2019) has recently highlighted how social / psychological structures can in fact play a major role in sustainable travel behaviour, and might be a feasible (if not necessary) alternative to conventional monetised (dis)incentive mechanisms. Sensibilisation approaches tend to align with planning objectives higher on the horizon pyramid of Figure 2, typically at the strategic level. The approaches are typically

unresponsive and **static**, targeting long-term changes in behaviour. Policy actions tend to be developed in a **centralised** fashion.

6.4 User acceptance

Finally, it's important to take into account how (dis)incentive mechanism might (negatively) affect road users. Concerns related to fairness and equity have recently been object of increased interest and investigation in mobility management, with public support (or lack thereof) being widely recognised as a key challenge for widespread implementation of incentive-based approaches. In this section we give a brief overview of how these aspects have been approached in literature.

6.4.1 Fairness and equity

A historical perspective on determining which factors play a role in public resistance to (dis)incentive approaches can found in the work of (Giuliano 1992). At the time, renewed interest in the problem of imposing monetary disincentives to ease peak hour congestion encountered strong opposition, as summarised in Table 4. The authors identified three main explanatory sources: i) difficulty in clearly communicating the advantages to the public; ii) widespread scepticism around the topic; iii) equity & fairness concerns.

Table 5: Reasons for opposing congestion pricing. (Giuliano 1992).

Reason	# of times cited in literature rev.
Scepticism/misunderstanding	5
Equity/fairness	4
Implementation problems	2
Right to travel	2
Pricing what was free	2
Tax resistance	1
Harmful to business	1
Privacy	1
Restriction of choice	1

Equity in monetized disincentive strategies is indeed a fundamental issue towards implementation: due to the different effects that a levied toll might have across different income classes, it is natural for road users to perceive direct monetary tolls as inherently unfair.

Several works in literature have since focussed on the issue of fairness, both in terms of collecting 'lessons learned' from implementation pilots (Taylor and Kalauskas 2010) and in analysing the trade-off between fairness and effectiveness of (dis)incentive mechanisms, its nature and its determining factors (Kristoffersson, Engelson, and Börjesson 2017)

Recent approaches have been attempting to include fairness directly as key performance indicator, leading to a class of incentive mechanisms which feature fairness-by-design, with promising results both in tradable credit schemes (D. Wu et al. 2012) and congestion charging (Baranzini, Carattini, and Tesauro 2021).

The issues of fairness and equity have thus far been mainly considered from a strategic/tactical planning level, and have been treaded in a strictly **centralised** fashion, as they rely on network-wide knowledge of the population demographic, the spatiotemporal composition of demand, etc.

6.4.2 Compliance

Low levels of public acceptability often call for enforcement strategies to ensure adequate levels of compliance. Technology-enabled enforcement strategies are quite well established in the state-of-practice, as the authors in (Staudinger 2009) and (Vermaat 2018) highlight. Technological enforcement can however lead to heightened privacy concerns (Elliott and Jennings 2009).

Interestingly, while some root causes of lack of compliance (perceived inequity, unfairness, …) bear a clearly centralised nature, relating to planning decisions at higher hierarchical levels, enforcement strategies are strictly operational. Typically **responsive**, enforcement approaches rely on real-time measurements to identify unruly road users, can be **dynamic** depending on the network conditions (e.g. average speed cameras alongside roadworks enforcing a safe speed limit to protect the workforce) and operate in a **decentralised** fashion, typically relying on local measurements and information.

6.5 Conclusions and key knowledge gaps

In this chapter we explored the state-of-the-art for (dis)incentive mechanisms in mobility management. In these concluding remarks we summarise our guiding questions, briefly detailing what was found from literature and which knowledge gaps we have identified.

- What are the fundamental objectives of incentive schemes in mobility management?

Incentive schemes have been employed across multiple levels of the planning pyramid, with objectives ranging from highly strategic (reduce car ownership, promote sustainable modes) to downright operational (buffer traffic outside of an incident area). Across the three axes employed for our literature review evaluation (centralisation/decentralisation, stasis/dynamism and responsiveness/unresponsiveness), a clear trend seems to appear: the closer the objectives are to operational planning, the more the approaches tend to exhibit responsive/dynamic properties. Decentralisation efforts, if present, appear exclusively in operational approaches.

- How are optimal values for (dis)incentives determined?

Methods for determining optimal values show considerable dependency on both i) the objectives of interest and ii) whether the (dis)incentive approach is monetary. Considerable research effort has been spent in developing single-objective approaches for monetary disincentive schemes, with optimality guarantees or conditions. Behavioural approaches, such as nudges, have received comparatively less attention in methodological research, although a clear trend for further development of both theoretical and practical applications of these approaches can be observed in the last ~5 years. When considering multiple objectives, potentially conflicting, various approaches have been proposed, ranging from computational heuristics to nonlinear optimization approaches. The issue of pareto-optimality when including directly conflictual objectives (e.g., maximising both efficiency *and* fairness) remains an open challenge.

- How can this arbitration be carried out through decentralized decision-making?

Decentralisation remains an unresolved challenge in literature. While some facets of incentive mechanisms are naturally decentralised (e.g. enforcement), we could not identify any efforts in literature concerning either decentralised computation of the optimal (dis)incentive values nor network-wide objective (re)formulation on the basis of decentralised actions.

The fundamental challenge of DIT4TraM is, indeed, filling this gap in literature through the development of innovative management schemes exhibiting decentralisation capabilities reminiscent of swarm intelligence.

7 Concluding remarks

The purpose of this review is to provide a basis for the theoretical developments in the remainder of WP2, and for the development of the algorithms for the pilot in Bordeaux (Task 7.2). The overall goal of WP2 is to develop incentive-based traffic control approaches for local bottlenecks in the context of various technological settings, with emphasis on the role of cooperation and distribution. This means that not only a traffic control problem has to be solved, but also the proper incentives need to be determined, and that the approach must match the features of the technological environment, including but not limited to its computational structure.

To have an overview of the relevant technologies and methods in the context of incentive-based traffic control, scientific literature in four main areas has been considered: (1) communication technologies and technological architectures for V2X, (2) data collection and state estimation for cooperative control, (3) control methods for cooperative traffic management at local bottlenecks, (4) incentive schemes for traffic and mobility management.

Within each of these subthemes, we formulated specific research questions and – at least to an extent – collected relevant answers via the literature scan. In this chapter, we summarize these questions, the corresponding answers, and the identified key gaps in literature.

Note that given the broadness of the topic, we have not intended to, nor were we able to, be exhaustive. More exhaustive surveys will be done on specific subtopics in a more targeted way in the remainder of WP2.

7.1 Communication technologies and technological architectures for V2X

The real-world implementation of the theories and algorithms developed in WP2 demands V2X technologies to enable the interoperation among multiple coexisting, heterogeneous networks. To assess the readiness of V2X technologies for such a task, we need to review the literature to answer the following questions:

- What are the recent achievements in the field of V2X communication technologies?

There has been a continuous progress in the field of V2X technologies ever since the original V2X technology (i.e., DSRC) was released in 1999. However, the speed of advancements of V2X communication technologies has increased dramatically since 2013, as it attracted both industrial and governmental funding. As of the start of 2022, there are two mainstream V2X technologies:

802.11 V2X and C-V2X, whose transceivers are now incorporated in newly manufactured vehicles. The state-of-the-art V2X technologies are comprised of C-V2X, further enhanced by 5G-NewRadio-V2X and mmV2X.

- What are the shortcomings of these technologies?

While with each generation of V2X come outstanding pros, there might also emerge some cons that were not present in previous versions. Some notable issues across different V2X technologies include limited coverage range and penetration rate, signal interference, expensive set-up costs, etc.

- What are the technical V2X requirements?

Basic requirements mainly concern safety and warning applications, while advanced requirements concern AI-enabled applications, like cooperative and automated driving and control. Each of these applications require specific latency (bitrate), reliability, penetration rate (line-of-sight), and capacity (throughput) that are discussed in further detail in this chapter.

- What combination of communication technologies can meet these requirements?

The literature recommends the coexistence of different generations of V2X as the way to overcome the shortcomings accompanied in different V2X technologies and meet its basic and advanced requirements. This is expected to lay a solid ground for the real-world implementation of the theories and algorithms that we will develop in WP2.

7.2 Data collection and state estimation for cooperative control

In assessing the data needs and capabilities for the development of incentive mechanisms for cooperative connected traffic at local bottlenecks, four key research questions arise:

Which sensor and communication technologies (or combinations thereof) are most suitable for realising (cost-) efficient and secure data collection and communication?

Many contributions suggest that a combination of different sensing techniques, onboard and roadside, provide the most promising opportunities to determine information for different cooperative applications in a cost-efficient fashion.

Which information is to be exchanged with which vehicles (or road-side systems) at which frequency and aggregation level to achieve the <u>*optimal trade-off between information exchange cost and performance*</u> *of the* *cooperative vehicle application (e.g., cooperative car-following and lane changing, cooperative intersection control, vehicle routing, …)?*

Numerous papers are based on approaches wherein the requirements in terms of data to be exchanged are determined by the (projected increase in) performance of the application that the data is catering for. This bears strong relevance for the information exchange protocols for the system planned in WP2. In the considered literature, reinforcement learning approaches are often employed to tackle this design problem.

Which methods are suitable for optimally estimating and predicting the state of the system, by combining the different available data sources?

The considered literature either uses classical traffic flow theory modelling in combination with filtering techniques or relies on data-driven approaches. While no comprehensive benchmarking papers have been considered, in designing the control approach in WP2 we believe it pivotal to match the requirements regarding the information stemming from the approach to the filtering method used.

How can anomalies in the data be detected, either due to sensor or communication failure or security breaches, and how can robust data collection and communication platforms be designed?

This question relates to the issue of security, which becomes of fundamental importance in 'beyond-pilot' applications. We only briefly considered this topic, mostly highlighting its relevance, but drew no fundamental conclusions contributing to WP2.

7.3 Cooperative traffic management methods

In the discussion of control methods for cooperative traffic management at local bottlenecks the main aspects of controller design are considered: the control objective, the inclusion of policy objectives, the traffic mechanism that is exploited to improve performance, the mathematical formulation of the control problem and its solution, and fairness of and the compliance with the instructed control solutions.

Traffic control approaches can be categorized in approaches that control traffic on a macroscopic level (such as ramp metering controlling the on-ramp flow) and approaches that control individual vehicles in terms of their trajectories. All traffic control approaches aim in the first place at optimizing the overall system performance, such as (a combination of) total travel time, fuel consumption, emissions etc. In addition, approaches operating at a microscopic scale typically aim to further optimize some vehicle-based performance measures, such as fuel consumption or comfort. The most suitable methodological approach for incentive-based control seems to be optimization-based, due to its flexibility in determining (possibly time-varying) control objectives and constraints. However, due to the relatively high computational complexity, there is a need for approaches that can tackle these problems efficiently.

In the transition from macroscopic control of manual vehicles to microscopic control connected and automated mobility, more methods that can cope with a wide range of mixed traffic, including manual vehicles and various levels of connectedness and automation, will be needed. From the perspective of traffic mechanisms, we identify a substantial need to align the macroscopic and microscopic views on traffic control.

Fairness was found to be of little relevance in the vast majority of approaches, appearing neither in the design nor in the evaluation phase of the proposed controllers. However, typically control at bottlenecks implies the prioritization of some traffic participants, and therefore might lead to reduced equitability. There is an opportunity for incentive-based control to contribute to the fairness of current-generation traffic management.

The lack of fairness, in combination with the fact that connected and automated vehicles are presumed controlled by advised (requested) trajectories may lead to non-compliance. While compliance for macroscopic controllers is typically ensured by roadside technology (fines), in the incentive-based control context, compliance finds no solid theoretical grounds. Development of ex post incentives might lead to a viable solution.

7.4 Incentive schemes

When devising mechanisms for cooperative connected traffic management, the following question was formulated as key guideline:

What are the fundamental objectives of incentive schemes in mobility management, how are optimal values for (dis)incentives determined, and how can this arbitration be carried out through decentralized decision-making?

Incentive schemes have been employed across multiple levels of the planning pyramid, with objectives ranging from highly strategic (reduce car ownership, promote sustainable modes) to downright operational (buffer traffic outside of an incident area). Across the three axes employed for our literature review evaluation (centralisation/decentralisation, stasis/dynamism and responsiveness/unresponsiveness), a clear trend seems to appear: the closer the objectives are to operational planning, the more the approaches tend to exhibit responsive/dynamic properties. Decentralisation efforts, if present, appear exclusively in operational approaches.

Methods for determining optimal values show considerable dependency on both i) the objectives of interest and ii) whether the (dis)incentive approach is monetary. Considerable research effort has been spent in developing single-objective approaches for monetary disincentive schemes, with optimality guarantees or conditions. Behavioural approaches, such as nudges, have received comparatively less attention in methodological research, although a clear trend for further development of both theoretical and practical applications of these approaches can be observed in the last ~5 years. When considering multiple objectives, potentially conflicting, various approaches have been proposed, ranging from computational heuristics to nonlinear optimization approaches. The issue of pareto-optimality when including directly conflictual objectives (e.g., maximising both efficiency and fairness) remains an open challenge.

Decentralisation remains an unresolved challenge in literature. While some facets of incentive mechanisms are naturally decentralised (e.g., enforcement), we could not identify any efforts in literature concerning either decentralised computation of the optimal (dis)incentive values nor network-wide objective (re)formulation based on decentralised actions.

The fundamental challenge of DIT4TraM is, indeed, filling this gap in literature through the development of innovative management schemes exhibiting decentralisation capabilities reminiscent of swarm intelligence.

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