Deliverable D3.2
Advances in Automated Vehicle Technology and Applicability to Railways

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Executive Summary

Road traffic is influenced by further digitalisation of vehicles towards highly automated and perhaps even autonomous vehicles. In road traffic, this exciting evolutionary step comes with the dream of harmonising road traffic and reducing the stochastic behaviour of individual vehicles and of road traffic as a whole.

For rail traffic, this evolutionary step might be used as a source of inspiration in an era where rail traffic professionals are designing a rail system with moving blocks and virtual coupling. This raises the question: “What applications, solutions and dynamics of automated car driving are applicability to the railway field?”. A question that can be answered in threefold.

Answer 1. Rail traffic can piggyback on developments in automated car driving.
The most obvious answer is that rail traffic can progress from developments in automated car driving, while preserving its own characteristics and specific requirements. ‘Piggybacking’ is of interest given that automotive is a mass market, which brings pressure on costs. This answer does not come as a surprise, since most of these developments are already underway.

Answer 2. What can be learned from the car centric approach on the road?
The road is car centric, with the ultimate ambition of ‘road traffic that organises and manages road traffic’. For railways it is a key responsibility of the infrastructure and rail traffic control system to provide safe passage, although more and more this is supported from equipment on the vehicles side. It might be interesting as an experiment in thinking to conduct a design exercise for railways with a strictly train centric approach to gain a better understanding of the possibilities and limitations of such an approach.

Answer 3. Rail traffic might investigate its own stochastic behaviour traffic.
The third answer is less obvious. Just as road traffic shows stochastic behaviour, this behaviour might be strengthened in railways with moving blocks and virtual coupling, given the diversity in trains, surroundings, train driver behaviour, et cetera. It is advised to study potential growth in stochastic behaviour in railways that comes with the introduction of virtual coupling and moving blocks. And in addition the stochastics that come with less predictable traffic demand from passengers ‘flowing’ in and out the trains.

Answer 4. Artificial Intelligence might strengthen stochastic behaviour in rail traffic.
We live in a digital era where Artificial Intelligence (AI) will become ubiquitous. Now, in railways (perhaps even more than on the road) stimuli will lead to a response, even if correct response is ‘no action at this time’. As such, AI will impact the fail-safe property of safety systems, which needs to be understood before rolled out. This is a serious challenge that needs to be studied. In addition it is advised to study the impact on stochastics in behaviour in rail traffic that comes with the introduction of AI in safety systems in rail traffic.

Abbreviations and acronyms

Abbreviation / Acronyms	Description
ACEA	European Automobile Manufacturers' Association
ADAS	Advanced Driver Assistance Systems
ADS	Automated driving system
AI	Artificial intelligence
ANPR	Automatic number plate recognition
ASIL	Automotive Safety Integrity Level
ATC	Automatic Train Control
ATO	Automatic Train Operation
ATP	Automatic Train Protection
ATS	Automatic Train Supervision
C2C	Car-to-car communications
C2X	Car-to-anything (else on the road) communication
C-DAS	Connected Driver Advisory Systems (for trains)
C-ITS	Cooperative intelligent transport system
DDT	Dynamic driving task
DSRC	Dedicated short range communication
EGNOS	European Geostationary Navigation Overlay Service
GLOSA	Green Light Optimised Speed Advise
GNSS	Global Navigation Satellite System
GoA	Grade of Automation in railways
IEEE802.11p	An approved amendment to the IEEE 802.11 standard to add WAVE, a vehicular communication system
ITS-G5	Commercially available short-range V2X technology based on the IEEE 802.11 standard and standardized in Europe as ETSI EN 302 663.
NHTSA	National Highway Traffic Safety Administration
ODD	Operational Design Domain
OEDR	Object and Event Detection and Response
PKI	Public Key Infrastructure
SAE	Society of Automotive Engineers
SAM	Seamless Autonomous Mobility, a system developed by Nissan together with NASA
SBAS	Satellite-based augmentation (such as EGNOS)
SSR	State Space Representation
TMS	(Rail) Traffic Management System
V2V	Vehicle-to-vehicle communication
V2X	Vehicle-to-everything (else on the road) communication
VANET	Vehicular ad-hoc network
VMS	Variable message sign
WAVE	Wireless access in vehicular environments
W-LAN	Wireless local area network

1. Background

The present document constitutes the Deliverable D3.2 “Advances in Automated Vehicle Technology and Applicability to Railways” in the framework of the Milestone MS3: “Automated Vehicle architectures lessons”.

2. Objective/Aim

MOVINGRAIL Work Package 3 'Communication Technology for Virtual Coupling' focuses on: (i) the identification of appropriate Virtual Coupling technical communication solutions and (ii) assessing and identifying proposals for Virtual Coupling technical communication solutions, while (iii) investigating the applications, solutions and dynamics of automated car driving and evaluating the applicability to the railway field. This document focuses on the third objective.

To appreciate the application, solutions and dynamics of automated car driving, first requires a deeper understanding of the characteristics of road traffic. It is against the backdrop of these characteristics that the application, solutions and dynamics of automated car driving can better be understood. From this understanding the applicability to the railway field will be assessed.

3. Structure of the analyses

New concept, systems nor their enabling technologies come out of the blue. They follow up on what has been in place before and still is operational nowadays. The path towards automated driving and cooperative intelligent traffic systems (C-ITS) follows this rationale.

Arnold Cornelis [1] has provided us with a metaphor for the evolutionary process in our society and systems. This metaphor builds on three stability layers as illustrated in Figure 1. We will use these three layers to position the concepts of automated driving and C-ITS to keep in mind that these concepts stand for an evolution, not a revolution.

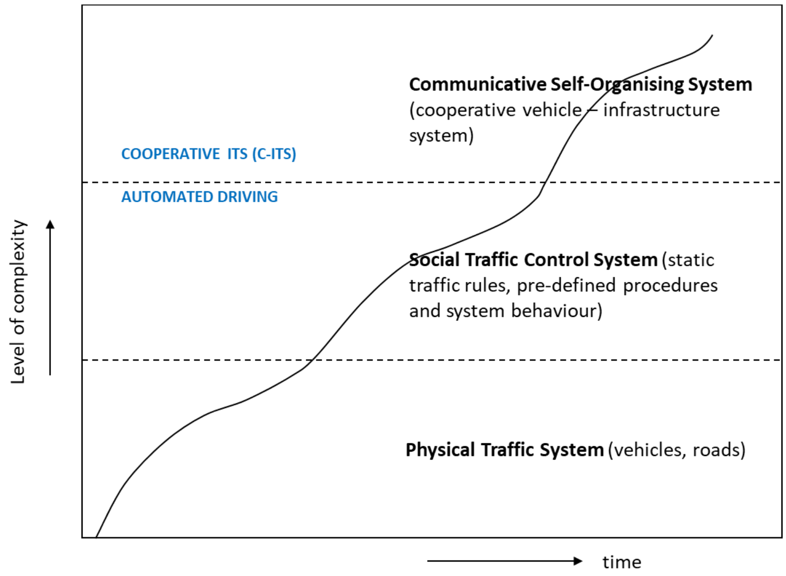

Figure 1. The continuous evolution of the road traffic system [25] in analogy of the three stability layers of Cornelis [1].

Since the advent of roads there is the physical traffic system, consisting of drivers, using vehicles on the road. Over the past decades, the physical quality of the vehicles and roads (road surfaces) has improved. Road traffic is guided, warned and instructed via static traffic signals.

On top of the physical traffic system, the social traffic system has been added both to the vehicle and road side. For vehicles, it more or less started with a person walking in front of a car waving a flag. From that point on, it has grown towards the advanced driver assistance systems (ADAS) of today enhancing active road safety and comfort of driving. In addition vehicle drivers are supported by navigation services fed by real-time traffic and (more and more) parking data for an efficient and comfortable trip.

At the road side static traffic signals have been followed up by:

- traffic signal control using, for instance, traffic lights and ramp meters;
- provisioning of information/advice/warnings/instructions using variable message signs (VMSs);
- dynamic access control using bollards, barriers and digital instruments (such as video based automatic number plate recognition – ANPR and electronic tags in combination with dedicated short range or near field communication).

Road operators have started to manage traffic on their roads using these instruments. Every step

forward has been secured by rules and regulations on the side of both the vehicle and road infrastructure.

Within the context created by traffic rules and regulations, as well as by traffic control and management, road users apply a form of self-organisation. Although all the provided services are sophisticated by themselves, the autonomy of individual vehicle drivers may not necessarily lead to an optimal traffic safety and efficiency, as the Braes Paradox exemplifies (Box 1).

The Braes paradox is stated as follows: "For each point of a road network, let there be given the number of cars starting from it and the destination of the cars. Under these conditions, one wishes to estimate the distribution of traffic flow. Whether one street is preferable to another depends not only on the quality of the road, but also on the density of the flow. If every driver takes the path that looks most favourable to them, the resultant running times need not be minimal. Furthermore, it is indicated by an example that an extension of the road network may cause a redistribution of the traffic that results in longer individual running times." See: https://en.wikipedia.org/wiki/Braess%27s_paradox

Box 1. Braes paradox

From this perspective, the third layer – the layer of communicative self-organising – is the logical next step with new concepts such as automated driving, cooperative intelligent traffic systems (C-ITS) and interactive traffic management. Concepts that all rely on a close interaction between the individual (egocentric) vehicle and its surroundings, as illustrated in Figure 2.

These concepts will be explored in order to recognise the "Advances in Automated Vehicle Technology" and assess the "Applicability to Railways". While analysing the advances in automated vehicle technology it is useful to consider in the analyses the enabling technologies regarding that are used for automated driving, C-ITS and interactive traffic management and the way they are integrated in the vehicle; a deeper level that might contain useful insights for the railways.

This gives the following structure of the analyses:

- Chapter 6 – automated driving;
- Chapter 7 – cooperative intelligent traffic systems (C-ITS);
- Chapter 8 – interactive traffic management;
- Chapter 9 – enabling technologies;
- Chapter 10 – stochastics in traffic flow conditions;
- Chapter 11 – conclusions (applicability to railways).

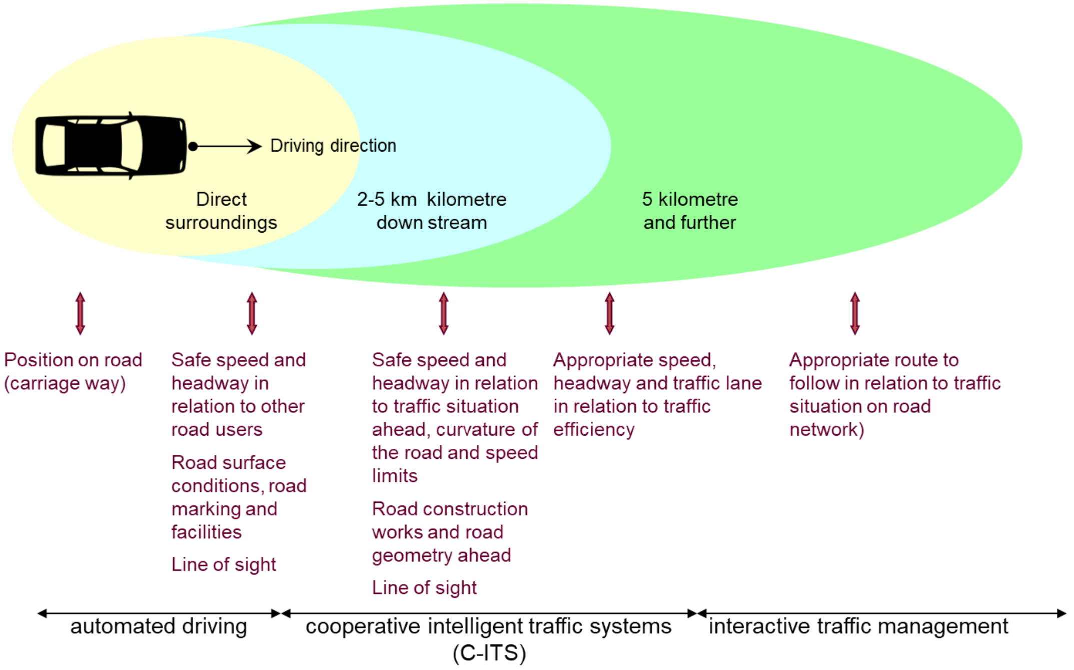

Figure 2. Concepts that rely on a close interaction between the individual vehicle and its surroundings.

4. Automated driving

4.1. Taxonomy of automated driving

To ensure a common understanding, first of all the taxonomy of automated driving and driving automation is set out. This paragraph heavily relies on the SAE International publication: *Surface Vehicle Recommended Practice - Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles*, J3016™ JUN2018 (issued 2014-01, revised 2018-06) [2].

Distinguished levels in driving automation

The notion of driving automation covers six discrete and mutually exclusive levels, as illustrated in Figure 3. Central in these levels are the respective roles of the (human) user and the driving automation system in relation to each other. Because changes in the functionality of a driving automation system change the role of the (human) user; they provide a basis for categorizing such system features.

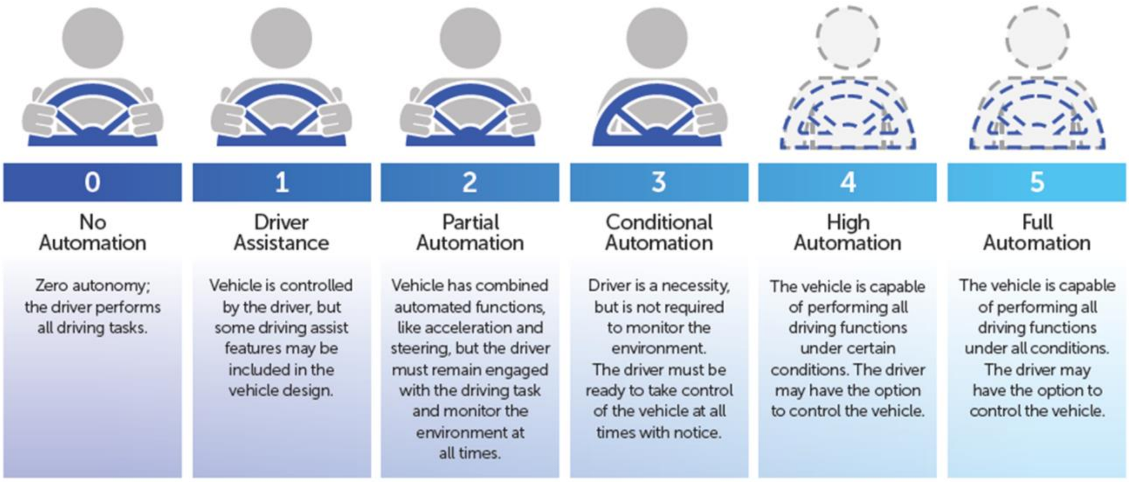

Figure 3.Six levels of driving automation [3].

Driving automation system

The enabling driving automation system builds on two subsystem, i.e. (Figure 4): active safety system and automated driving system [2].

Active safety systems

'Active safety systems are vehicle systems that sense and monitor conditions inside and outside the vehicle for the purpose of identifying perceived present and potential dangers to the vehicle, occupants, and/or other road users, and automatically intervene to help avoid or mitigate potential collisions via various methods, including alerts to the driver, vehicle system adjustments, and/or active control of the vehicle subsystems (brakes, throttle, suspension, etc.).' [2]

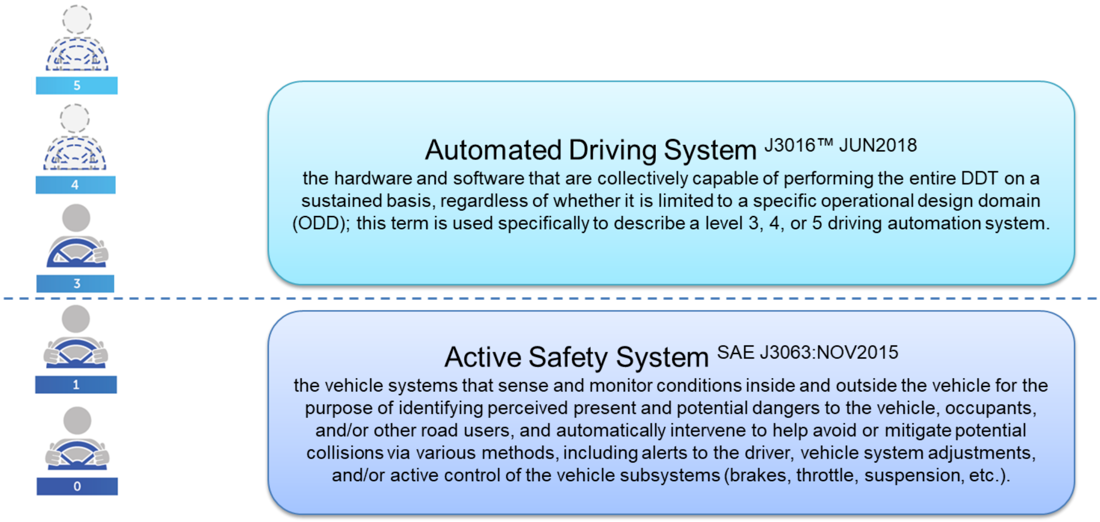

Figure 4. Two sets of subsystems within the driving automation system.

Automated driving systems

Automated driving systems (ADS) concerns the hardware and software that are collectively capable of performing the entire dynamic driving task (DDT) on a sustained basis, regardless of whether it is limited to a specific operational design domain (ODD). This set of subsystems is used specifically to describe a level 3, 4, or 5 driving automation system (see Figure 3).

Essential for automated driving is the focus on all of the real-time operational and tactical functions required to operate a vehicle in on-road traffic. This concerns without limitation functions such as:

- lateral vehicle motion control via steering (operational);
- longitudinal vehicle motion control via acceleration and deceleration (operational);
- monitoring the driving environment via object and event detection, recognition, classification, and response preparation (operational and tactical);
- object and event response execution (operational and tactical);
- manoeuvre planning (tactical);
- enhancing conspicuity via lighting, signalling and gesturing, etc. (tactical).

The strategic functions, such as trip scheduling and selection of destinations and waypoints, are excluded. These functions are supported by (connected) automotive navigation services. These services are used by a vehicle driver to find direction in a vehicle. It typically uses a satellite navigation device to get its positional data which is then correlated to a position on a road. When directions are needed routing can be calculated. On the fly traffic information can be used to adjust the route.

Figure 5 shows a schematic view of the full driving task and the operational, tactical, and strategic functions of driving.

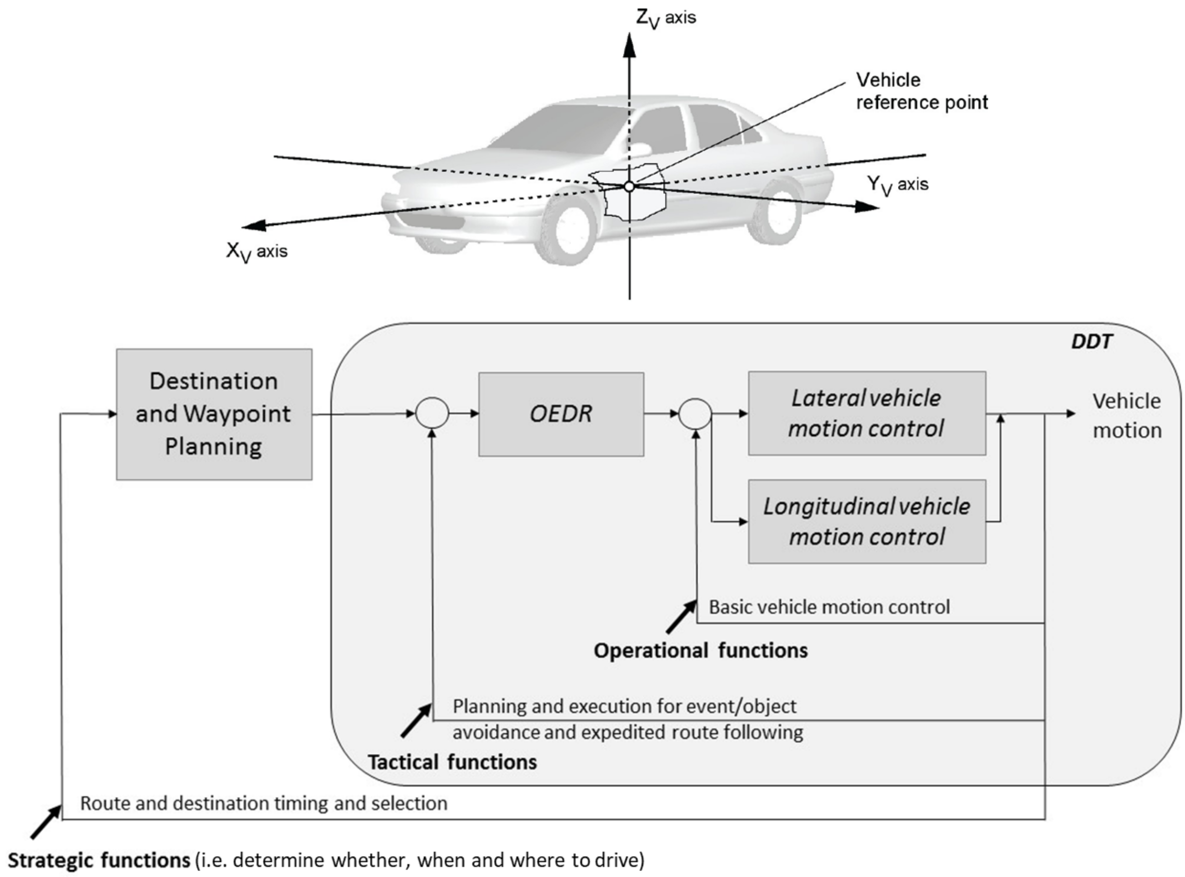

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Figure 5. Schematic (not a control diagram) overview of driving task showing the dynamic driving task (DDT) portion of the full driving task (source: [derived from [2]).

OEDR in this figure stands for Object and Event Detection and Response, the set of subtasks of the DDT that include:

- monitoring the driving environment (detecting, recognizing, and classifying objects and events);
- preparing to respond as needed;
- executing an appropriate response to such objects and events, i.e.: as needed to complete the DDT and/or the required DDT fall back.

DDT Fall-back function
After the occurrence of one or multiple DDT performance-relevant system failure(s), depending on the level of driving automation , either the vehicle driver / user or the DDT itself should respond in order to achieve a minimal risk condition.

The DDT and the DDT fall-back are distinct functions, and the capability to perform one does not necessarily entail the ability to perform the other. Level 3 ADS, for instance, is capable of performing the entire DDT within its ODD, but does not need to be able to perform the DDT fall-back in all situations that require it. Level 3 ADS requires a fall back-ready user (i.e. vehicle driver), which recognises a vehicle failure and responds to that, or responds to an ADS-request to intervene to the DDT.

At levels 4 and 5, however, the ADS itself must be capable of performing the DDT fall-back and achieving a minimal risk condition.

These fall-back options are illustrated in Figure 6.

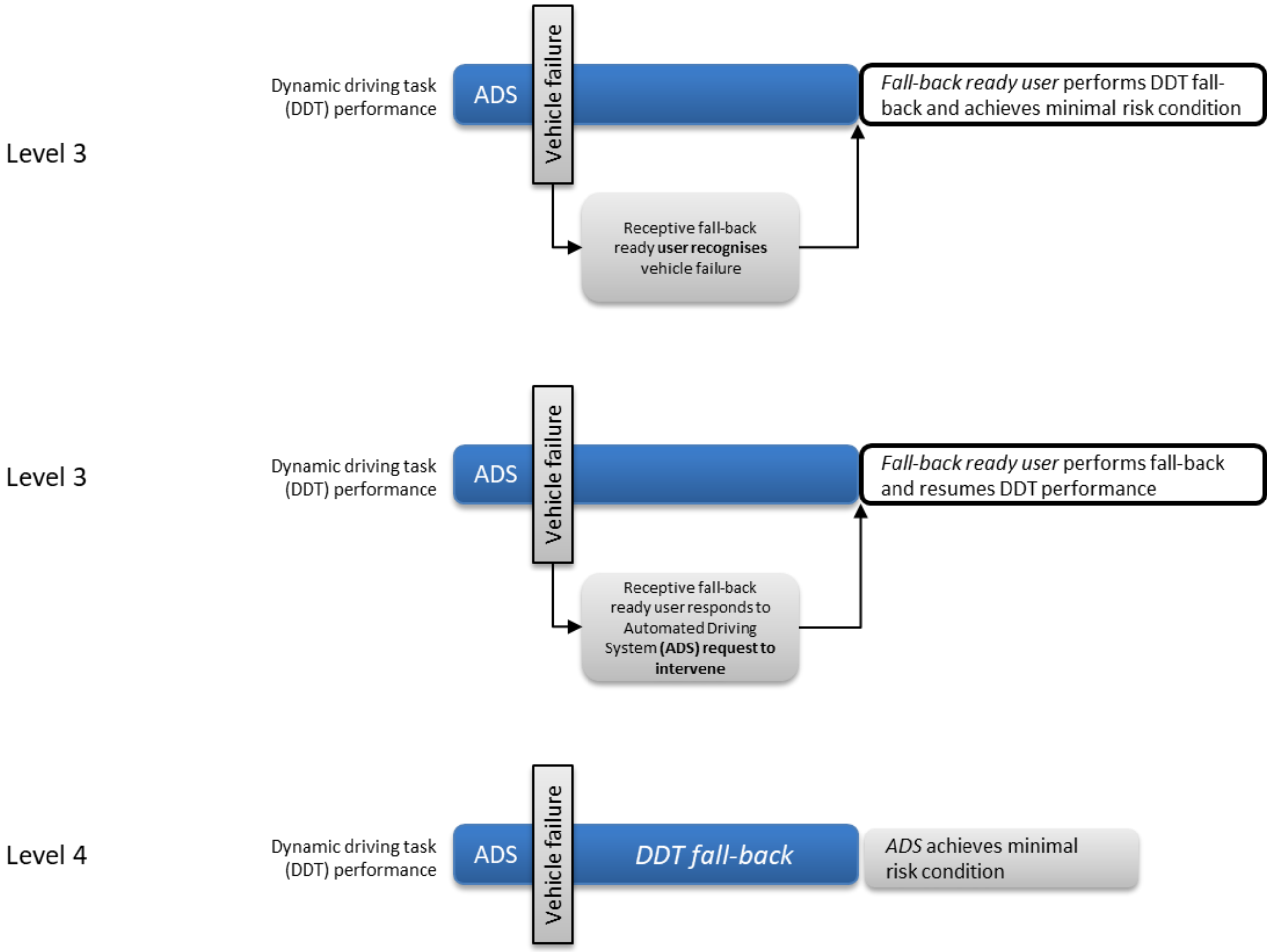


Figure 6. Sample use case sequences for fall-back after vehicle failure (derived from [2]).

Six levels in driving automation more in-depth
Table 1 summarizes the six levels of driving automation in terms of the required subsystems, the ODD and the fall-back responsibility.

Level	Name	Narrative definition	DDT		DDT fallback	ODD
			Sustained lateral and longitudinal vehicle motion control	***OEDR***		
Driver* performs part or all of the *DDT						
0	**No Driving Automation**	The performance by the *driver* of the entire *DDT*, even when enhanced by *active safety systems*.	*Driver*	*Driver*	*Driver*	n/a
1	**Driver Assistance**	The *sustained* and *ODD*-specific execution by a *driving automation system* of either the *lateral* or the *longitudinal vehicle motion control* subtask of the DDT (but not both simultaneously) with the expectation that the *driver* performs the remainder of the *DDT*.	*Driver* and *System*	*Driver*	*Driver*	Limited
2	**Partial Driving Automation**	The *sustained* and *ODD*-specific execution by a *driving automation system* of both the *lateral* and *longitudinal vehicle motion control* subtasks of the *DDT* with the expectation that the *driver* completes the *OEDR* subtask and *supervises* the *driving automation system*.	***System***	*Driver*	*Driver*	Limited
***ADS* ("*System*") performs the entire *DDT* (while engaged)**						
3	**Conditional Driving Automation**	The *sustained* and *ODD*-specific performance by an *ADS* of the entire DDT with the expectation that the *DDT fallback-ready user* is *receptive* to *ADS*-issued *requests to intervene*, as well as to *DDT performance-relevant system failures* in other *vehicle* systems, and will respond appropriately.	*System*	***System***	*Fallback-ready user (becomes the driver during fallback)*	Limited
4	**High Driving Automation**	The *sustained* and *ODD*-specific performance by an *ADS* of the entire *DDT* and *DDT fallback* without any expectation that a *user* will respond to a *request to intervene*.	*System*	*System*	***System***	Limited
5	**Full Driving Automation**	The *sustained* and unconditional (i.e., not *ODD*-specific) performance by an *ADS* of the entire *DDT* and *DDT fallback* without any expectation that a *user* will respond to a *request to intervene*.	*System*	*System*	*System*	**Unlimited**

Table 1. Six levels of driving automation from a more technical perspective [2].

4.2. The context for an automated driving vehicle

Automated driving in a specific Operational Design Domain (ODD)

A relevant element in the definition of automated driving systems is that their performance can be limited to a specific operational design domain (ODD). ODD represents the 'operating conditions under which a given driving automation system or feature thereof is specifically designed to function, including, but not limited to, environmental, geographical, and time-of-day restrictions, and/or the requisite presence or absence of certain traffic or roadway characteristics' [2].

Level 1 to level 4 ADS features are subject to limited ODDs. These limitations reflect the technological capability of the driving automation system. For example, level 4 ADS dedicated vehicles that operate in enclosed courses have existed for many decades as people movers and airport shuttles. The ODD for such vehicles is very simple, well-controlled, and physically enclosed (vehicle operates on a fixed course; physical barriers prevent encroachment; protected from external events, weather, etc.). This highly-structured and simple ODD makes it

technologically less challenging to achieve level 4 driving automation.

However, a level 3 ADS feature that operates a vehicle on open roads in mixed traffic, and does so in environments that include inclement weather, faces a significantly higher technological bar in terms of ADS capability by virtue of the more complex and unstructured ODD.

Figure 7 illustrates the orthogonality of ODD in relation to the levels of driving automation.

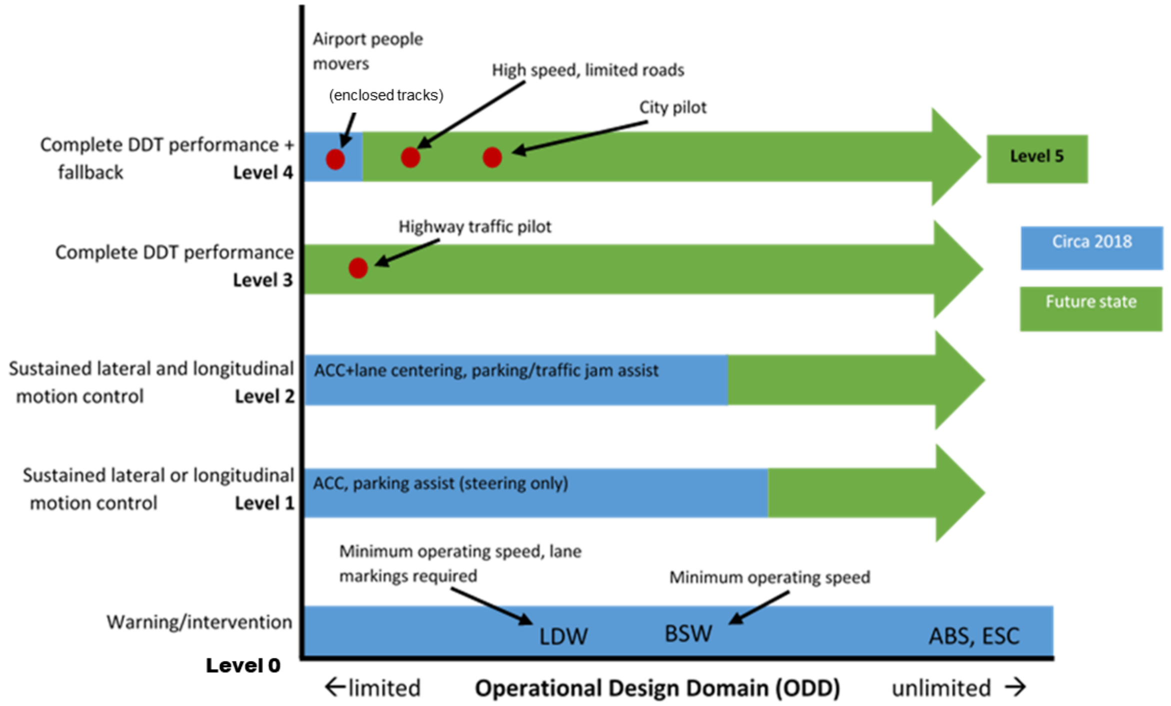


Figure 7. Operational design domain (ODD) in relation to driving automation levels.

Automated driving on open roads in mixed traffic against inclement weather conditions
The ultimate challenge for automated driving lies in driving on open roads in mixed traffic against inclement weather conditions. This requires behaviour of the vehicle that is constantly tuned to: (i) the type of road on which it is driving, (ii) the road surface conditions, (iii) the current and evolving traffic situation on that road and (iv) the current incidents and events on and along that road. To understand the complexity it is good to have a better look at the road network.
The road network as we know it, is the results of a growth process of many decades if not centuries. The result of this process is an extremely fine graded road network in which a layered structure can be recognised. This structure is illustrated in Figure 8.

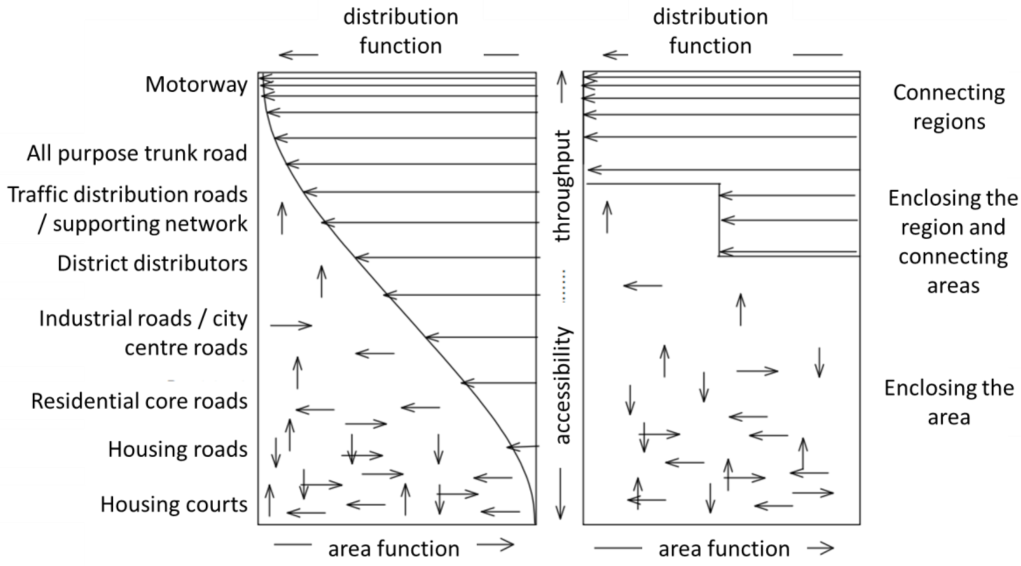


Figure 8. Layered structure in the road network[1].

In the end, all roads have a combined function of throughput and accessibility. The emphasis on one of these functions or the balance between these functions, determines the traffic characteristics on a specific road. Roads with an area function and thus an emphasis on accessibility are characterised by crisscrossing, multi-modal road traffic and lower driving speeds. Multi modal implies in this case motorised traffic, cyclists and pedestrians and trams. Roads with a distributions function and thus an emphasis on throughput are characterised by singular driving directions, separations of vulnerable road users (cyclists and pedestrians) from motorised traffic and high(er) driving speeds. Figure 9 is another, more schematic way to illustrate this.

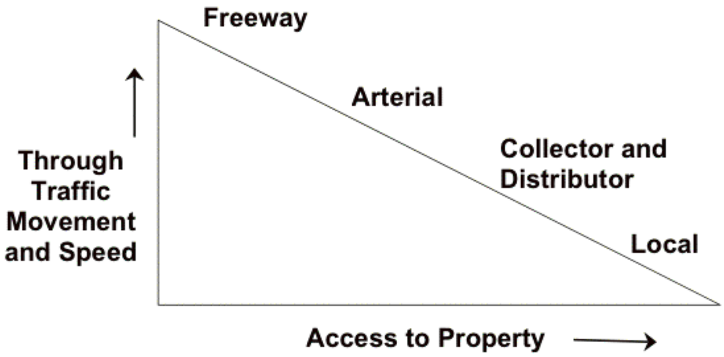


Figure 9. The hierarchy of roads categorizes roads according to their functions and capacities[2].

A more simple way to illustrate the complexity of the road network and the corresponding challenge for automated driving, is using snapshots from real life (Figure 10).

1 https://www.swov.nl/feiten-cijfers/factsheet/principes-voor-veilig-wegontwerp
2 https://en.wikipedia.org/wiki/Hierarchy_of_roads

Throughput *Distribution* *Accessibility*

Figure 10. Snapshots from real life illustrate the various characteristics of road traffic.

4.3. Dispatch function to guide automated driving on open roads

With the introduction of automated driving a new entity will be introduced that dispatches an ADS-equipped vehicle(s) in driverless operation [2], as illustrated in Figure 11. For example, 'a fleet of level 4 closed campus ADS-dedicated vehicles is placed into service by a driverless operation dispatching entity, which engages the ADS for each vehicle after verifying its operational readiness and disengages the ADS when each vehicle is taken out of service' [2].

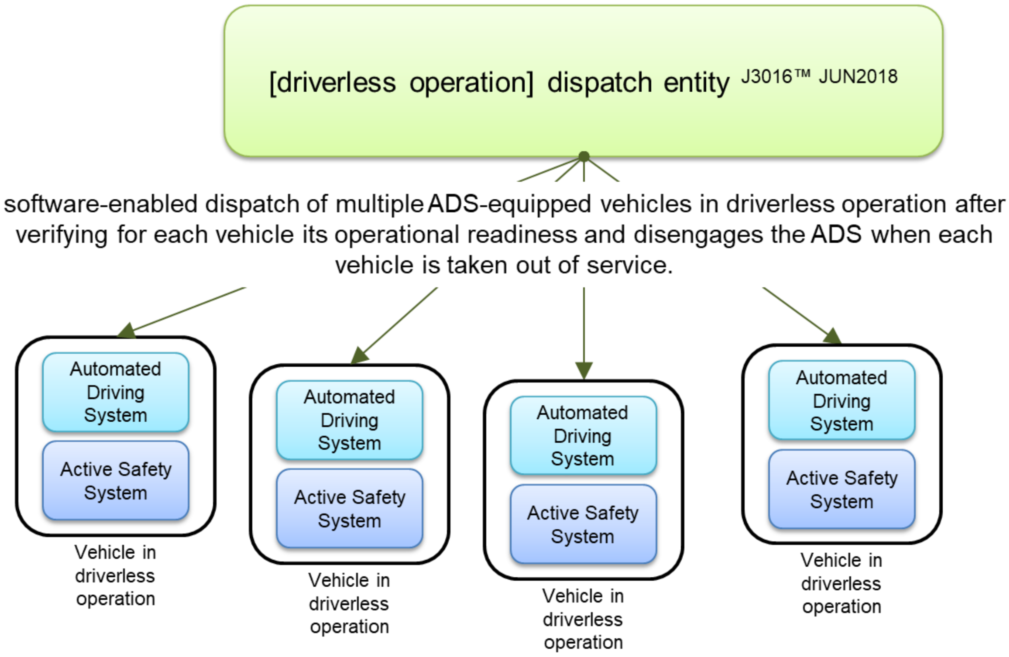


Figure 11. Remote control over driverless operations using a dispatch entity.

Another realistic example of a dispatching entity is Nissan's "Seamless Autonomous Mobility (SAM)" system developed with NASA to realize a fully autonomous mobility. SAM partners in-vehicle artificial intelligence (AI) with remote human support to help driverless autonomous vehicles make decisions in unforeseen and somehow unpredictable situations such as obstructions on the road. SAM also gathers information of all vehicles into the Cloud and build the knowledge of in-vehicle AI. The idea behind SAM is that it 'will enable millions of autonomous vehicles operate safely and smoothly on the road sooner with human support' [26].

4.4. Automated driving on roads versus railways

What can we learn from a high level comparison between road and railways?

Active safety

Where active safety on the road is rather vehicle centric, for railways it is a key responsibility of the infrastructure and rail traffic control system to provide safe passage, although more and more this is supported from equipment on the vehicles side. It might be interesting as an experiment in thinking to conduct a design exercise for railways with a strictly train centric approach to gain a better understanding of the possibilities and limitations of such an approach.

Automated driving

Automated driving is not a new concept for railways, where the concept of Automatic Train Operations (ATO) is being developed. ATO uses Grades of Automation (GoA) to distinguish the various levels as illustrated in Figure 12.

Railways

Road vehicle	Grade of Automation	Type of train operation	Setting train in motion	Stopping train	Door closure	Operation in event of Disruption
1	GoA 1	ATP with driver	Driver	Driver	Driver	Driver
3	GoA 2	ATP and ATO with driver	Automatic	Automatic	Driver	Driver
5	GoA 3	Driverless	Automatic	Automatic	Train attendant	Train attendant
	GoA 4	UTO	Automatic	Automatic	Automatic	Automatic

ATP - Automatic Train Protection   ATO - Automatic Train Operation

Figure 12. Four levels of Automatic Train Operations [29].

Coming from the schematic view of autonomous road vehicle driving task (see Figure 5) a similar schematic view for railways might look like as illustrated in Figure 13.

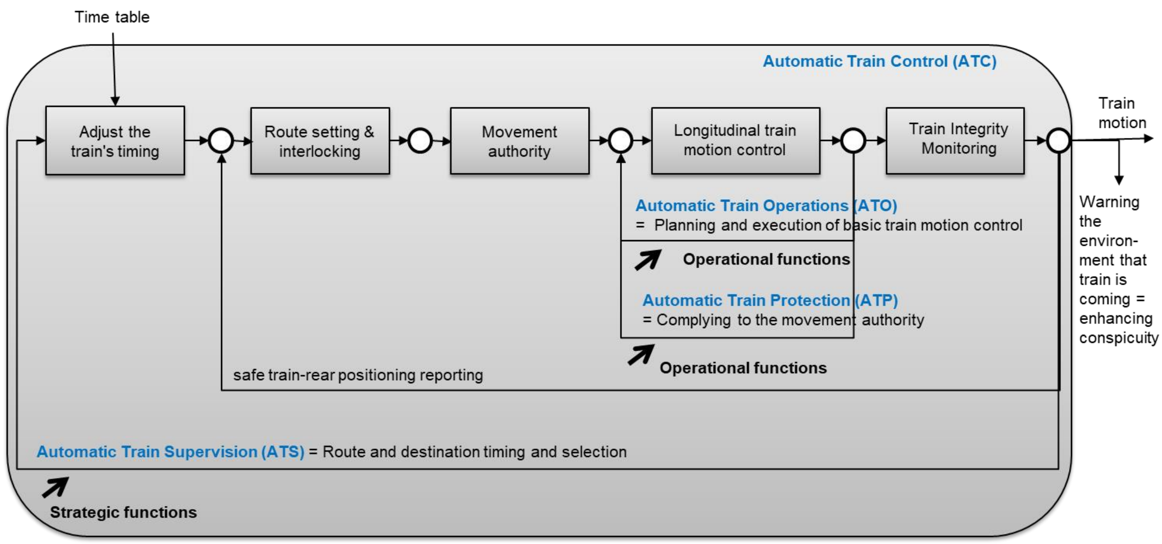


Figure 13. Schematic (not a control diagram) view of the train driving task, including the automated elements.

Operational Design Domain

Where automated driving within an ODD is seen as a limitation to overcome in road traffic, railways naturally works with a strict ODD being the railway network. The various networks for tram (streetcar), metro, train and sometimes even high-speed lines are separated from each other. And only trams have to deal with mixed traffic since part of their network is out onto roads that also feature cars, cyclists and pedestrians.

Dispatch function

Introducing a dispatch function is also not a new concept for railways. On the contrary, it is – in the form of rail traffic control - essential for systems such as railways with a strict ODD (the rail network), a predefined timetable (strategic) and strict safety requirements given the high driving speeds, long braking distances in combination with limited manoeuvrability (only longitudinal) of trains. Here road traffic makes a step towards the way of working of railways.

Strategic function of automated driving

A crucial difference is that where the strategic function is left to the vehicle user on the road, it is an essential function of timetable design and provides the context for every individual train in the form of its timetable and of the full set of trains in the form of conflict free paths over the railway network (see Figure 13).

An element in the suggested experiment in thinking to conduct a design exercise for railways with a strictly train centric approach, might be to assess whether this might affect the timetable design method and, if so, if this has an added value.

Tactical and operational function of automated driving

The high driving speeds, long braking distances and limited manoeuvrability of trains make that the tactical and operational function of automated driving work with a different geographical horizon (see Figure 13). Monitoring the direct driving environment is less relevant for trains since the possibilities to avoid an obstacle by laterally moving away from it are not available. Avoiding an obstacle via an emergency brake is hard due to the long braking distance.

Monitoring the driving environment response preparation and response execution is a task that can only be done via vehicle to infrastructure communications and more and more via vehicle to vehicle communication. This is touched upon in chapter 5.

Conspicuity

For unsupervised, level crossing of rail and road or for trams (streetcars) in general it is useful that a train or trams warns cooperative road users that is it coming via C-ITS (see chapter 5).

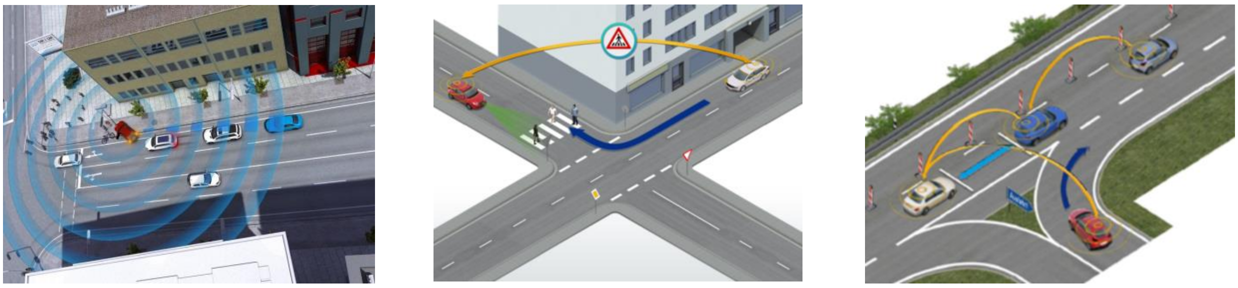
5. Cooperative intelligent traffic systems (C-ITS)

5.1. Distinguished angles for C-ITS

The added value of C-ITS can be looked upon from various angles, amongst which: safe driving, efficient driving, and safe & efficient road traffic. All three angles will be elaborated, after which C-ITS will be positioned against automated driving.

5.2. Enhancing safe driving

Following the rationale of the CAR 2 CAR Communication Consortium [4], virtual coupling of road vehicles can enhance road safety on three levels, as illustrated in Figure 14.



Awareness Driving | Sensing Driving | Cooperative Driving

Figure 14. Virtual coupling of motor cars can enhance road safety on three levels [4].

The three levels will be explored more in-depth. Virtual coupling of motor cars is here referred to as V2X, which stand for vehicle-to-everything communications. ‘Everything’ in road traffic can be other vehicles, the road infrastructure, cyclists and pedestrians, and, in the end, devices and the smart grid.

Added value of Awareness Driving

V2X based information and warning services support road users in driving with foresight and raise the awareness for potential risks which are not yet visible. The virtual coupling consists of individual vehicles exchanging status data via V2X communication, e.g. the position, speed, driving direction or special incidents such as a vehicle defect.

Following the CAR 2 CAR Communication Consortium, examples of awareness-based information and warning services are [4]:

- intersection collision warning;
- emergency vehicle warning;
- dangerous situation warning;
- stationary vehicle warning;
- traffic jam warning;
- pre-/post-crash warning.

Added value of Sensing Driving

On top of status data, V2X capable vehicles (or more generally C-ITS capable road users) can share observations gained by sensors, and advanced environmental information. In this way non-communicating road users are also taken into account and protected in different traffic situations. As such, traffic participants are warned against dangers they cannot yet perceive.

Following the CAR 2 CAR Communication Consortium, examples of sensing- based information and warning services are [4]:

- overtaking warning;
- extended intersection collision warning;
- vulnerable road user warning;
- cooperative adaptive cruise control;
- long-term road works warning;
- special vehicle prioritisation.

Added value of Cooperative Driving
In addition to status and sensor data, cooperative road users can also provide intention data, allowing them to interact intelligently and even to coordinate their behaviour in complex traffic situations. These notifications are an important requirement for the long-term goal of highly automated and autonomous driving.

Following the CAR 2 CAR Communication Consortium, examples of cooperative services are [4]:

- (static or dynamic) platooning;
- area reservation;
- cooperative merging;
- cooperative lane change;
- cooperative overtaking.

5.3. Enhancing efficient driving

Vehicle convoy formation
Vehicles forming convoys by temporary and location-based virtual coupling can help to enhance efficiency of driving and can be beneficial for traffic efficiency. Two good examples of situations in time and place where convoy formation can help are signalised intersections and traffic jam heads.

Vehicle convoy formation at signalised intersections
Deadlocks on intersections ('nodes') in the road network are prevented by signalising critical intersections. At such intersections road users and thus vehicles have to stop and are queued up during the red signal time (Figure 15). In the end, clusters of vehicles are formed that move over this part of the road network.

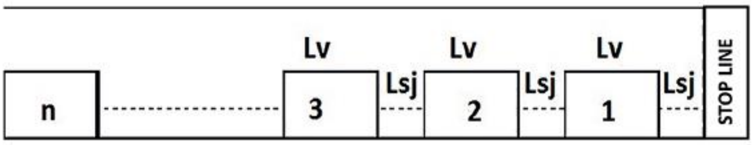


Figure 15. Basic presentation of vehicles at a signalized lane [5].

The added value of virtual coupling of motor cars on or around signalised intersections is that it can help to prevent gaps from occurring between accelerating vehicles at green light. By (temporarily) forming a convoy of virtually coupled vehicles the moment the traffic lights turns to green for a specific direction, the volume of vehicles that can pass the green light can be maximised. Convenient for the vehicle drivers, helpful for a better utilisation of the road capacity.

Vehicle convoy forming at the head of a traffic jam

Empirical observations show a positive relationship between the speed in congestion and the queue discharge rate, i.e. the amount of vehicles that drive away from the traffic jam head [6]. Additional experiments showed that variations in driver behaviours can account for the capacity drop and moreover the stochasticity of desired accelerations at the head of the congestion (even without lane changing) [7].

The capacity drop can be illustrated as follows:

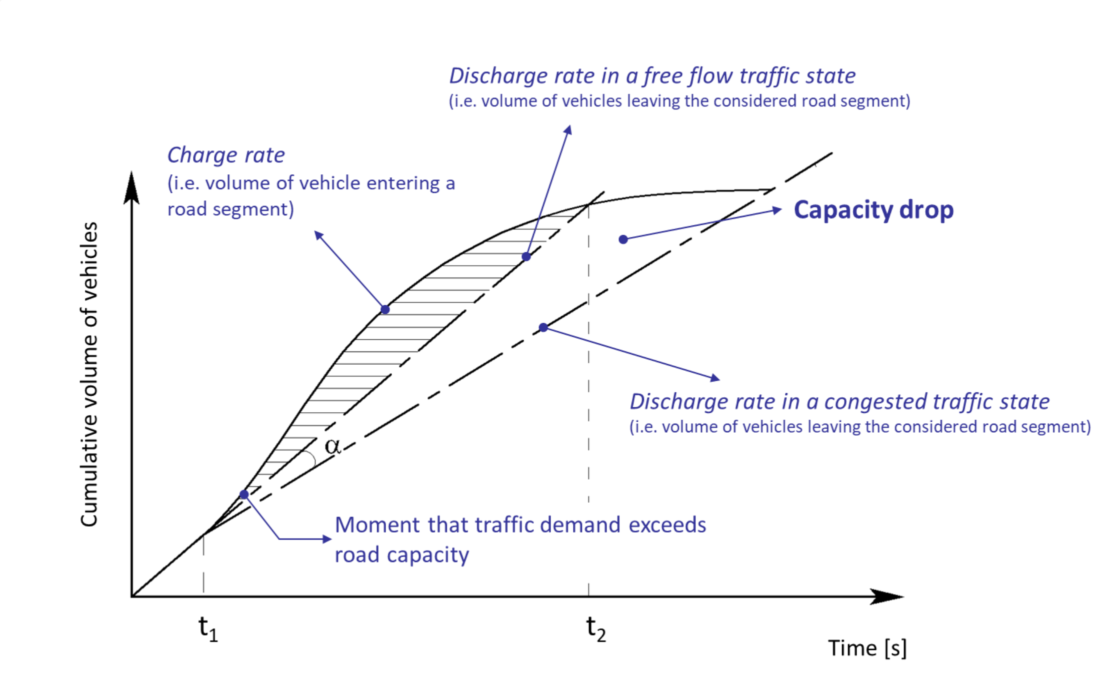


Figure 16. The capacity drop illustrated (derived from [8]).

Box 2. The capacity drop illustrated.

The added value of virtual coupling of motorcars at the head of a traffic jam is that it can help to harmonise the accelerations and prevent gaps from occurring between accelerating vehicles while discharging from the queue (traffic jam). Again, convenient for the vehicle drivers, helpful for a better utilisation of the road capacity.

Although convoy formation offers useful opportunities it is not so much a focus point of attention, yet. The spontaneous character does not make it trivial to control from a road safety perspective. The first step in this direction might be platooning.

Platooning

With the envisaged growth of (container) transport by road in the coming years, better utilising the road infrastructure is a necessity. Truck platooning is the linking of two or more trucks in convoy, using connectivity technology and automated driving support systems. These vehicles automatically maintain a set, close distance between each other when they are connected for certain parts of a journey, for instance on motorways. The truck at the head of the platoon acts as the leader, with the vehicles behind reacting and adapting to changes in its movement –

requiring little to no action from drivers. In the first instance, drivers will remain in control at all times, so they can also decide to leave the platoon and drive independently [9].

Successful realization of such platoons requires a digital matching platform that organizes the composition of the platoons [10]. As such, truck platooning builds on the commitment and adoption of shippers and carriers to actively support and enable truck platooning. In other words, truck platooning requires the creation of a community (Figure 17).

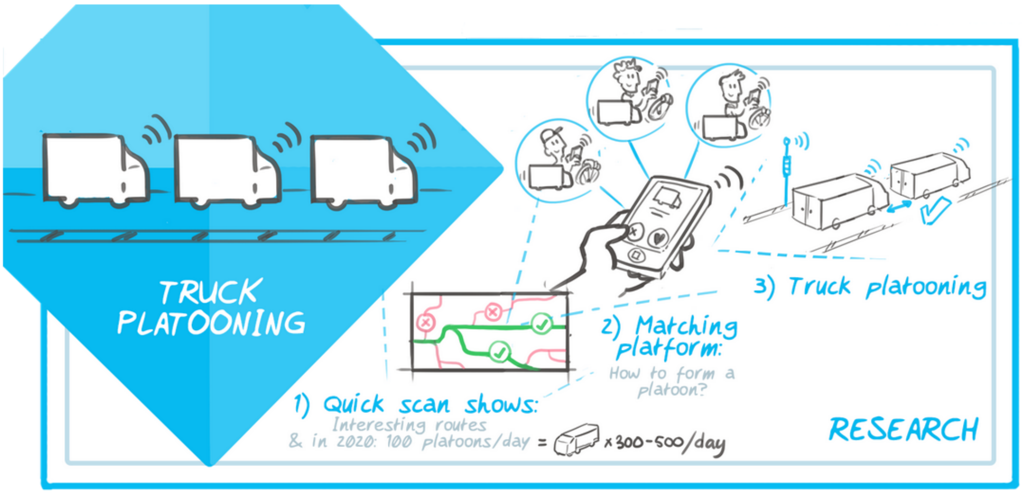


Figure 17. The idea of truck platooning illustrated 10].

Opportunities
The opportunites for truck platooning can be found in (Figure 18) [9][10]:

- savings - trucks drive in each other's slipstream, which results in savings on fuel consumption, and therefore on costs and CO_2 emissions;
- improved traffic flow – the assumption so far is that truck platooning is a more efficient way of using the road, which provides better traffic flow and therefore saves travel time and provides a higher reliability of road transport. This assumption needs to be challenged in metropolitan areas with a finer grade and often densely used motorway network characterised by short distances between the slip-on and slip-off roads;
- more efficient use of labour - truck platooning requires a different deployment of drivers. It allows drivers to undertake other tasks, such as administrative work or making calls. The other way around, the driving range of trucks can be extended in certain situations;
- increased road safety – the assumption is that automated driving in a platoon is safer due to the reduction of human errors (the main cause of accidents). Braking occurs automatically and immediately; the trucks following the lead vehicle only need one-fifth of the time a human would need to react. Again, an assumption that needs to be challenged in real-life;
- data sharing and automation - collaborating parties share data on the matching platform with which good and fast platoons can be created. Sharing data gives new possibilities for optimisation of truck (cargo space) usage.

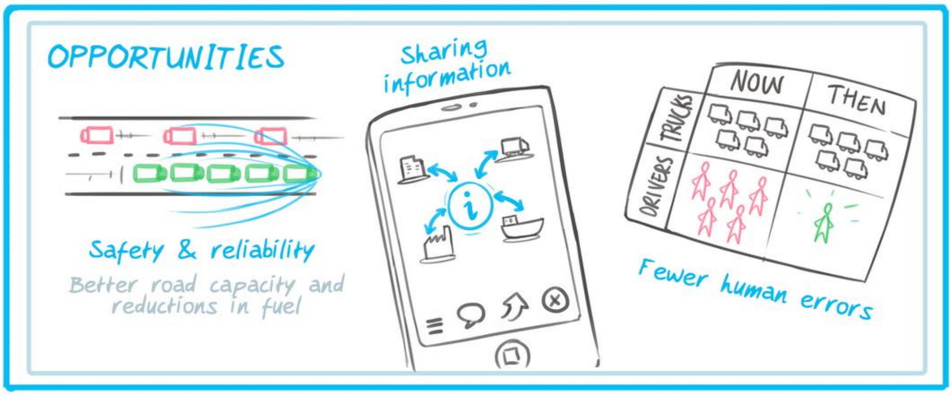


Figure 18. Opportunities of truck platooning build on data sharing and automation [10].

Challenges

To exploit the opportunities offered by truck platooning a series of technical and non-technical challenges need to be overcome. The next main technical challenges are [10]:

- introducing multi-brand platooning (up to automation level 2 as defined by the SAE, see Table 1) with the driver still ready to intervene. After all, carriers and shippers need to be able to platoon with trucks of different brands
- subsequently, allowing the driver of a trailing truck to rest might come under consideration. Full autonomous trucks will only come later.

Some of the non-technical challenges are [9][10]:

- sharing data - shippers and carriers need to be willing to collaborate and share the data that is required for a successful matching of trucks. Data on, for example, which transports are available for platooning and what their destination is. With this data the order in which the trucks will drive in the platoon, for example, can be established;
- large-scale - to make the implementation of the technology financially feasible, large-scale application is needed;
- driver deployment - how can the truck driver use his or her time efficiently during platoon driving?
- adjusting regulations - regulations must be adjusted to be able to roll out truck platooning.
- European harmonisation - it should be possible to drive across Europe on motorways (thus crossing national borders) with multi-brand platoons, without needing any specific exemptions.

At a European level, a road map has been set out for truck platooning, as illustrated in Figure 19 [9].

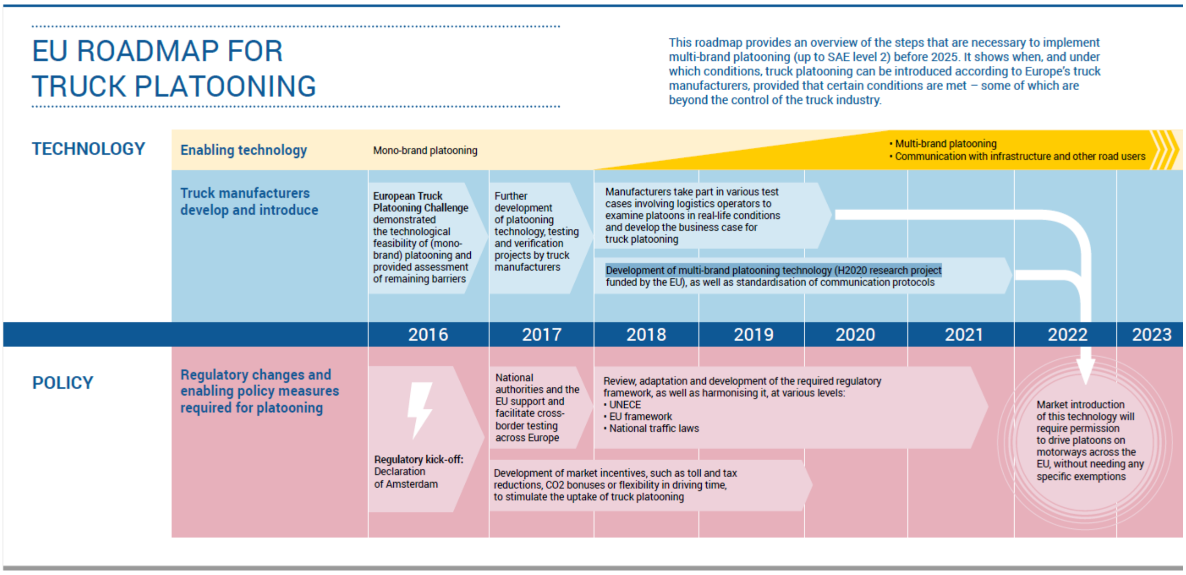


Figure 19. EU road map for truck platooning [9].

5.4. Enhancing safe and efficient road traffic

Through the C-Roads Platform, authorities and road operators join together to harmonise the deployment activities of cooperative intelligent transport systems (C-ITS) across Europe. The goal is to achieve the deployment of interoperable cross-border C-ITS services for road users[3].

So far, there seems to be a broad consensus on the C-ITS services that should be included in early deployment [11]. These services have been depicted in Table 2.

Virtual coupling between a vehicle and a traffic signal controller can include a 'Green Light Optimized Speed Advisory' (GLOSA) service. Such a service is able to reduce both CO_2 emissions and fuel consumption by giving drivers speed recommendations when approaching a traffic light.

A good example of such an approach is provided by the City of Copenhagen, which intends to prioritise motorised traffic and especially heavy traffic (truck and busses) on a subset of the corridors on the municipal road network, as depicted in Figure 20 [12]. Combining traffic signal optimisation over this ring road with a GLOSA service introduces an eco-driving service into a city that strives to be CO_2 neutral in 2025.

[3] https://www.c-roads.eu/platform/

Day 1 C-ITS services list
Hazardous location notifications: • Slow or stationary vehicle(s) & traffic ahead warning; • Road works warning; • Weather conditions; • Emergency brake light; • Emergency vehicle approaching; • Other hazards. **Signage applications**: • In-vehicle signage; • In-vehicle speed limits; • Signal violation / intersection safety; • Traffic signal priority request by designated vehicles; • Green light optimal speed advisory; • Probe vehicle data; • Shockwave damping (falls under European Telecommunication Standards Institute (ETSI) category 'local hazard warning').
Day 1.5 C-ITS services list
• Information on fuelling & charging stations for alternative fuel vehicles; • Vulnerable road user protection; • On street parking management & information; • Off street parking information; • Park & ride information; • Connected & cooperative navigation into and out of the city (first and last mile, parking, route advice, coordinated traffic lights); • Traffic information & smart routing.

Table 2. ITS services that should be included in early deployment [11]

Figure 20 Selected routes where motorcar traffic will be prioritised in Copenhagen [12].

One step further, virtually coupled vehicles can form a convoy (or cluster) that communicates with the traffic signal controller. The traffic signal controller assesses whether the vehicle convoy can cross without stopping. As a result, the green phase may be prolonged to accommodate that the entire convoy passes the intersection together or an early warning about an inevitable stop is given.

Extending this principle over full corridors helps to reduce stop-go traffic and as such emissions of noxious gasses.

A good example for this approach comes from the Green4Transport project in Hamburg[4].

For the system to reach its maximum potential, it is necessary to properly predict all different types of traffic lights, that is, also adaptive traffic lights where signals may change with lead times as short as 1 second. This is currently, an unresolved challenge for road traffic.

[4] https://www.hamburg-port-authority.de/en/themenseiten/green4transport/

5.5. C-ITS versus Automated driving

Enhanced usage of road capacity and enhanced road safety come together in the road map in terms of automated and even autonomous vehicles, as indicated in the CAR 2 CAR Communication Consortium services and use case roadmap (Figure 21).

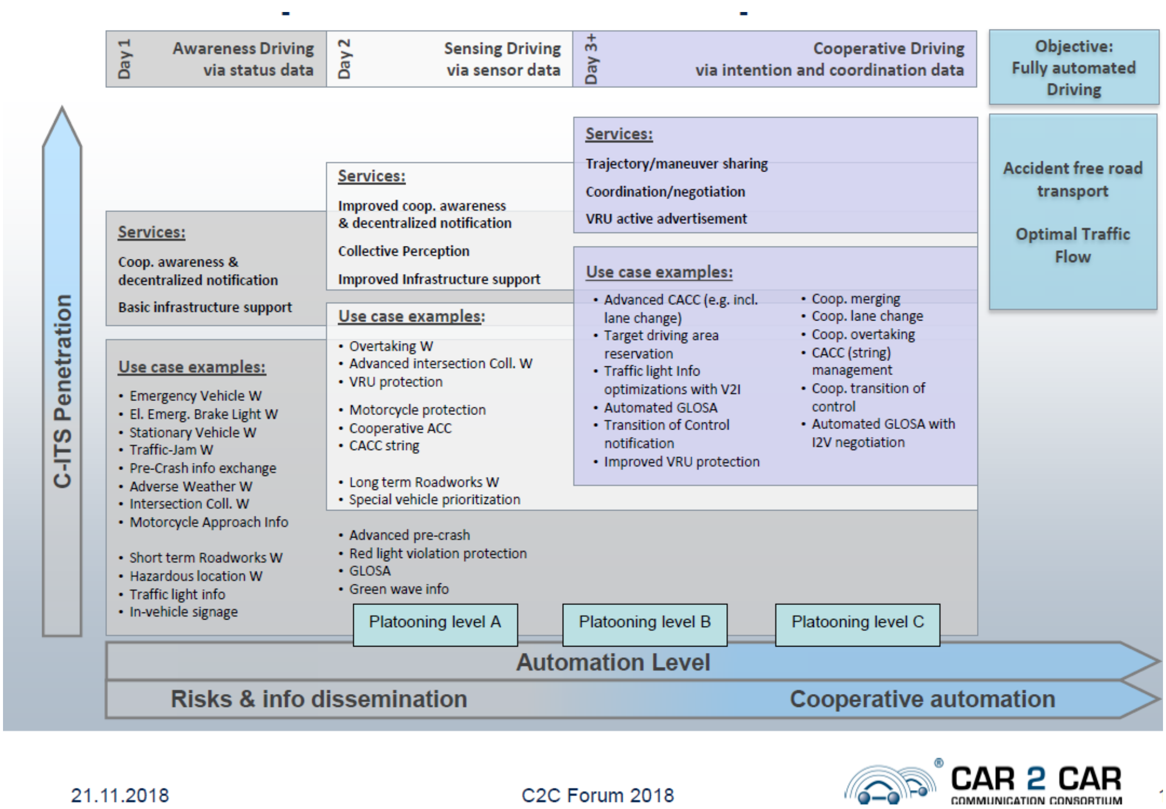


Figure 21. CAR 2 CAR Communication Consortium services and use case roadmap [4].

5.6. C-ITS on roads versus railways

What can we learn from a high level comparison between road and railways?

Enhancing safety of driving

As stipulated in paragraph 4.4, C-ITS can bring a value for 'enhanced conspicuity ' in railways. Trains can warn, via C-ITS, cooperative road users that is it coming, while it approaches an unsupervised, level railway crossing. Trams (streetcars) can communicate its intentions via C-ITS directly with cooperative road users in its direct surrounding. This is the obvious usage of C-ITS for railways.

One step further, it might be interesting as an experiment in thinking to conduct a design exercise to embed C-ITS and cooperative driving (see Figure 14) in interlocking to gain a better understanding of the possibilities and limitations of such an approach.

Enhancing efficiency of driving

Within the context of the designed and implemented timetables, it might be interesting as an experiment in thinking to conduct a design exercise to assess whether cooperative driving (see Figure 14) can help in aligning the driving speeds of individual trains dynamically to the current,

mutual train position on the railway network and as such prevent stop&go manoeuvres and contribute to the energy consumption of trains. To some extent this already exists on the railways with Connected Driver Advisory Systems (C-DAS).

A second opportunity might lie in the interaction along platforms with travellers with the sole objective to come to an efficient process of alighting and subsequently entering the train carriages. C-ITS can help to spread travellers over the platform such that the concentrations of travellers on the platform match the availability of empty seats places in the carriages of the train.

Enhancing safe and efficient traffic

Both vehicle convoy forming and platooning might contain interesting elements for railway traffic. Convoy forming, for instance, in case multiple trains have to leave a railway station about the same time. Platooning in constructing trains dynamically by virtual coupling.

Again, it might be interesting as an experiment in thinking to conduct a design exercise with convoys and platooning on railways.

Predictability of traffic signals

There is a significant difference between ‘road traffic lights’ and ‘railway signals’ given that their objective differs. Railways signals have a 100% safety function. As such, the behaviour of a railway signal is predictable only changing to more permissive aspects (with the exception of very special emergencies).

Road traffic lights have a combined traffic efficiency and traffic safety function. This makes that the ideal traffic light controller is traffic responsive, which makes them less predictable.

6. Interactive traffic management

6.1. Why traffic management?

Although the holy grail for road traffic might be ‘road traffic that organises road traffic’, reality shows that there are serious limitations to self-organization of traffic in networks. What we can learn from day-to-day traffic monitoring is [14]:

- dilute traffic organizes itself efficiently;
- if traffic load increases, efficient self-organization stagnates;
- different phenomena self-organize which reduce throughput.

The main reason for stagnating self-organisation can be deducted from the fundamental diagram, as illustrated in Figure 22 [1]. It appears that distribution of traffic seriously impacts network production. Spatial inhomogeneity leads to reduced production. The underlying phenomena that strengthen spatial inhomogeneity, are illustrated in Figure 22 as well.

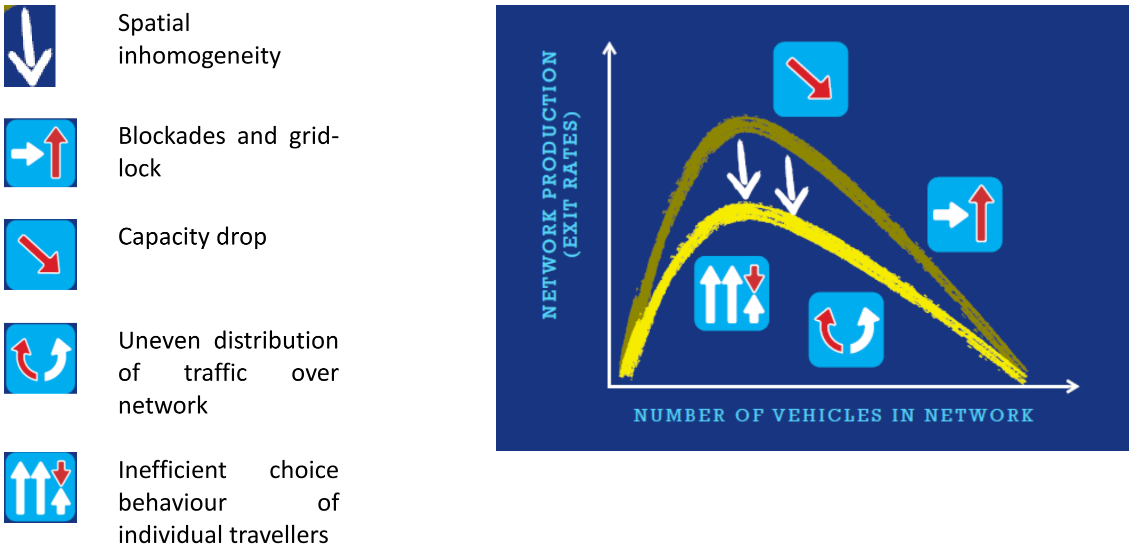


Figure 22. Characterising stagnating network production [14].

6.2. Traffic management approached from the road side

Isolated traffic management measures

Traffic management on the road network aims at preventing these phenomena to occur. It aims to prevent blockage and grid locks, to increase throughput when and where possible, to come to an even distribution of traffic and to reduce inflow when and where required.

Let us take a closer look at an example: the removal of wide moving jams (see box 3) and the ‘prevention of a capacity drop’ caused by these jams.

To come to a more in-depth understanding of the characteristic of motorway traffic, such traffic can be regarded looked upon as a complex, physical process where with the elementary particles on motorways are as vehicles. Coming from this perspective, Boris Kerner developed between 1996 and 2002 [9] the so-called three-phase traffic theory focusing mainly on the explanation of the physics of traffic breakdown and resulting congested traffic on highways between 1996 and 2002 [9]. Kerner describes three phases of traffic, i.e. (Figure 23):

- Free flow (i.e. a stationary, homogeneous flow). These states displayed uniform flow which remain stationary for as long as a few minutes;
- Wide moving jams (i.e. density waves). In these states, vehicle velocity was nearly constant, but waves in flux (and therefore density) were observed propagating through the line of cars. Distinct, often uncorrelated waves were observed in separate lanes;
- Synchronised flow (i.e. essentially nonstationary and inhomogeneous flow). In these states no clear pattern emerges.

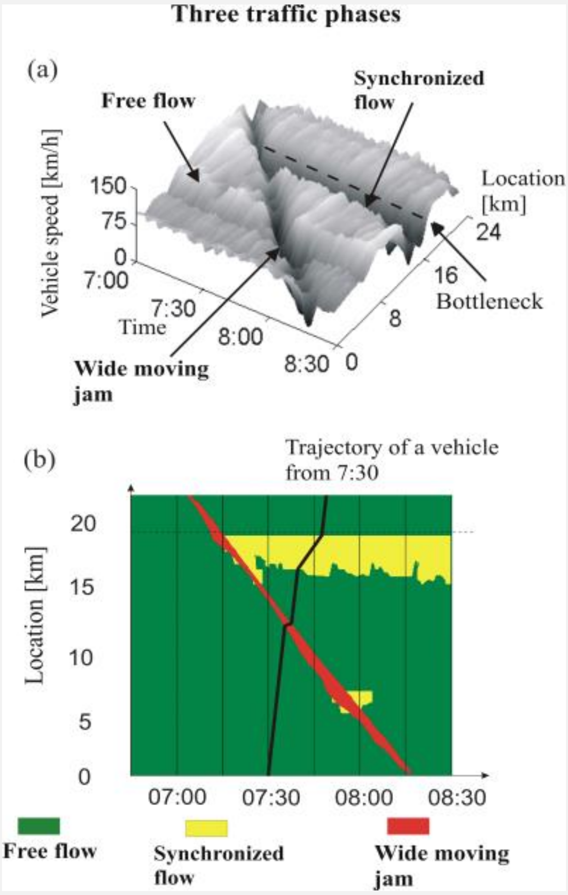


Figure 23. Three phases of road traffic according to Kerner [15].

Box 3. 'Wide moving jams' explained [15].

Regular traffic management uses road side sensors, intelligence and actuators to do the following, namely (Figure 24):

- monitor and assess the traffic state using induction loops;
- use intelligence to reason and translate, e.g. via an algorithm like *Specialist*:

- reason what the inflow reduction towards the wide moving jam should be to shorten and eventually dissolve it;
- translate the required inflow reduction into dynamic speed limits on the upstream road segment;

- set the dynamic speeds limits using variable message signs (VMSs).

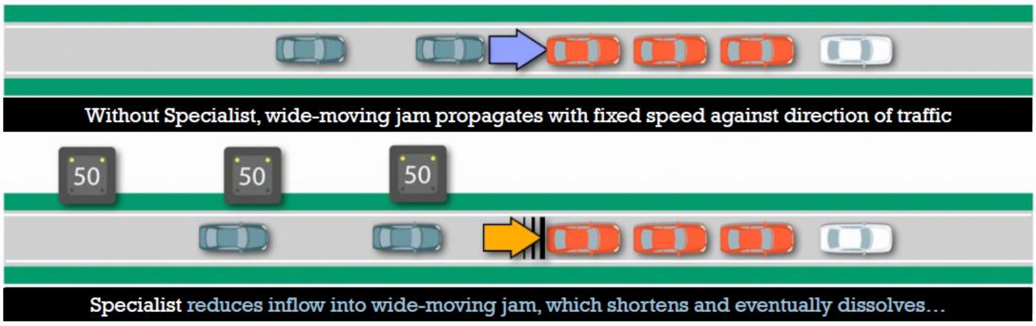


Figure 24. Example: removal of wide moving jams using Specialist [14].

Coordination of traffic management measures

On a road network level traffic management measures need to be coordinated to harmoniously counteract the occurring phenomena that strengthen spatial inhomogeneity. After all, isolated measures have their limitations, such as [8]:

- measures cannot always be deployed effectively for a long time due to (policy) constraints resulting in limited buffer space;
- the effect of a measure can be reduced by problems elsewhere in network;
- the effect of a single measure can be insufficient.

Network-wide coordination of isolated measures implies the joint and coherent deployment of measures to raise the isolated measures above their limitations and ensure that buffer-space all over the road network is used properly.

Again, removal of wide moving jams can be used as a good example of such coordination. Reducing the inflow to a wide moving jam can also be done using ramp metering. This brings in the necessity to coordinate ramp-metering over the consecutive slip-on roads to realise the required reduction of the inflow towards the wide moving jam. In addition coordination is required between ramp metering and the downstream intersections to prevent blocking back effects due to a growing queue on the slip-on road. Such coordination is illustrated in Figure 25 This example shows how available buffers can be used to reduce inflow into bottleneck on the motorway and prevent on-set of congestion on the urban arterials. Which buffers to use in the coordination depends on their relation with the bottleneck (i.e. the traffic volume that passes the intersection and is heading towards the motorway, indicated by %). The size of the buffers depends on the policy objectives (function of road, public transit, etc.) and the prevailing network traffic conditions.

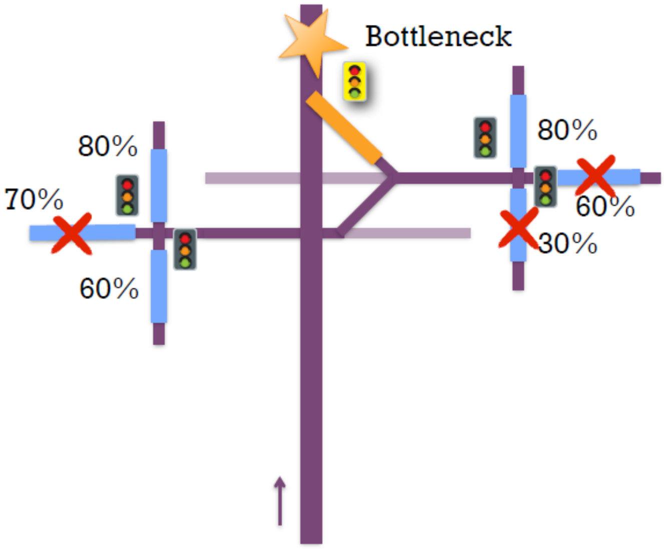


Figure 25. Example of coordination in terms of isolated measures to use storage space on upstream ramps to meter over a longer stretch (coordinated ramp-metering) [14].

6.3. What is interactive traffic management?

With the introduction of connected navigation services in mobile and in-vehicle devices, road traffic management is no longer the solitary playing field for road operators. Commercial service providers assist their users in finding the shortest, fastest or most scenic route from their origin to destination in a traffic responsive way. An optimal usage of the road network nowadays requires a well-structured cooperation between road authorities, service providers and automotive industries. A cooperation that needs to be developed, making use of:

- newly defined business models which create a win-win-win for both public and private stakeholders and road users;
- a mutual service request to come to coordinated assistance of road users by the various road authorities and service providers;
- new data exchange protocols to provide technical solutions throughout the complete traffic management (value) chain.

Together, this is called interactive traffic management or cooperative traffic management, as illustrated in Figure 26. A new concept that is under development in European platforms such as TrafficManagment2.0 (https://tm20.org/) and C-ROADS (https://www.c-roads.eu/platform.html) and various national initiatives. An absolute challenge for interactive traffic management to succeed is to overturn the Braes paradox (see Box 1).

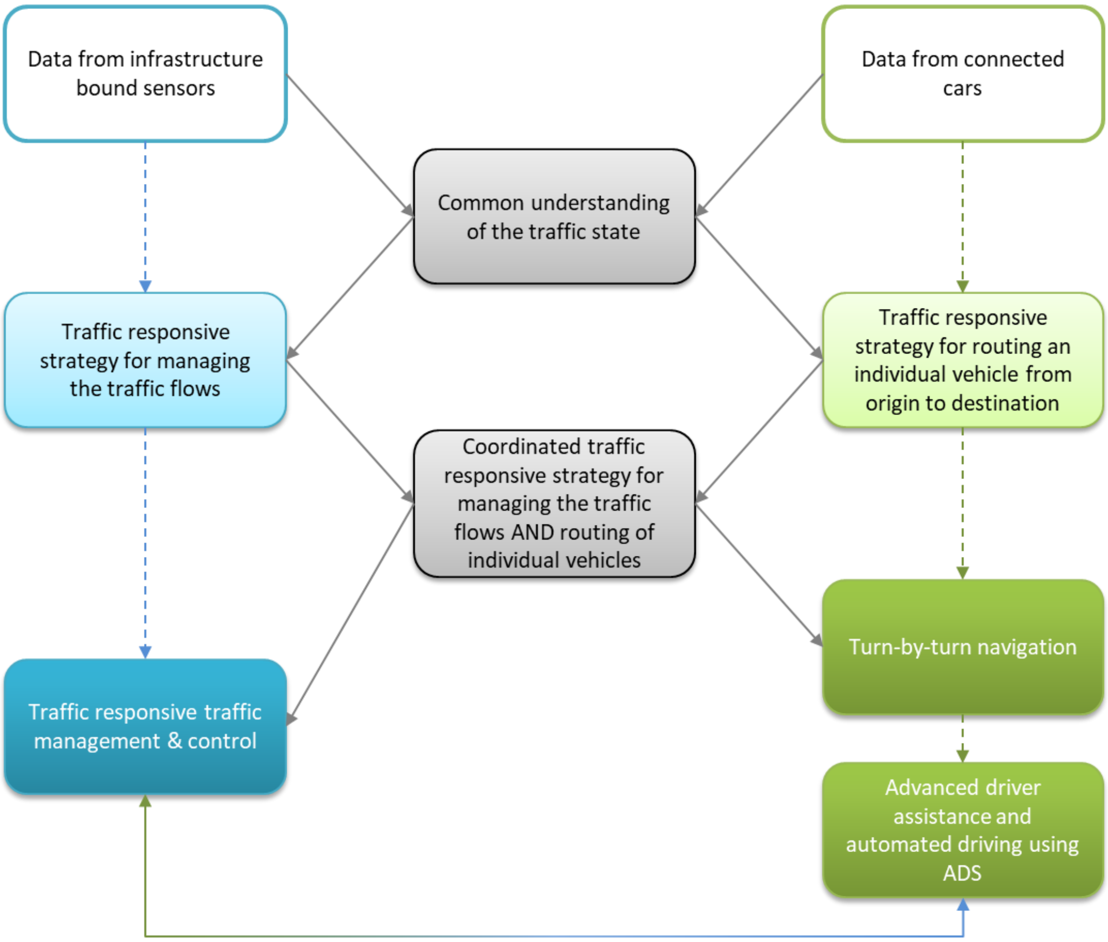


Figure 26. The concept of interactive traffic management illustrated.

6.4. Interactive traffic management on roads versus railways

What can we learn from a high-level comparison between road and railways?

A complex issue in road traffic is the openness of the system and the variations and thus unpredictability of the traffic demand. Interactive traffic management as such is all about preventing congestion to occur with the corresponding capacity drop as additional penalty, or at least postponing the moment congestion will occur.

The openness of railways is perhaps not so relevant to the traffic demand of trains, since the trains are fitted in an overall timetable. The openness of railways is more connected to the travellers that use the train as a crucial link in their journey from origin to destination. What railways might learn from interactive road traffic management is how to avoid the crowds on the platforms to grow to a size that can hardly or even not at all be handled by the train. This might be done by managing the flow of passenger dynamically by: (i) enhancing the outflow (alighting the train, leaving the platform and station), (ii) reducing or tempering the inflow to the station, platform and in the end train and (iii) by distributing the travel demand over time and over the platform (see C-ITS suggestion in paragraph 5.6).

The impact of this suggestion is illustrated in Figure 27.

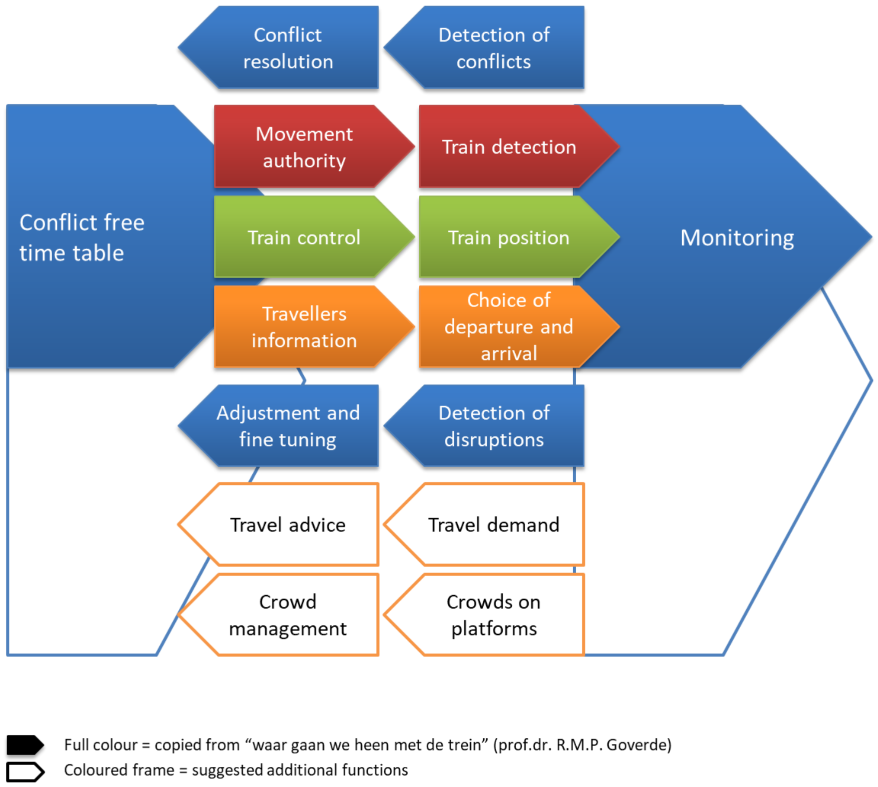


Figure 27. Proactive rail traffic management [27] plus suggested additional functionality.

The overall impression is that there is a high level of synergy between interactive road traffic management and the long-term aspirations of the emerging rail Traffic Management Systems (TMS). This impression needs a more in-depth analyses since the structures for interactive road traffic management on the road and in railways are in development.

7. Enabling technologies

7.1. The core enabling technologies

Now we have a better understanding of the added value of virtual coupling of motor cars, it is time to make a step towards the technology required for virtual coupling. Virtual coupling of vehicles on roads (Figure 28) uses five building blocks, i.e.:

- radio for communication (cellular, Wireless LAN);
- 'visuals' to scan the direct surroundings (LIDAR, radar, video, ultrasound);
- localisation (GNSS, odometer, gyroscope and a digital map);
- security to gain trust in received messages (PKI based certificates);
- intelligence to handle the stochastic elements.

Each of these building blocks will be explored more in-depth.

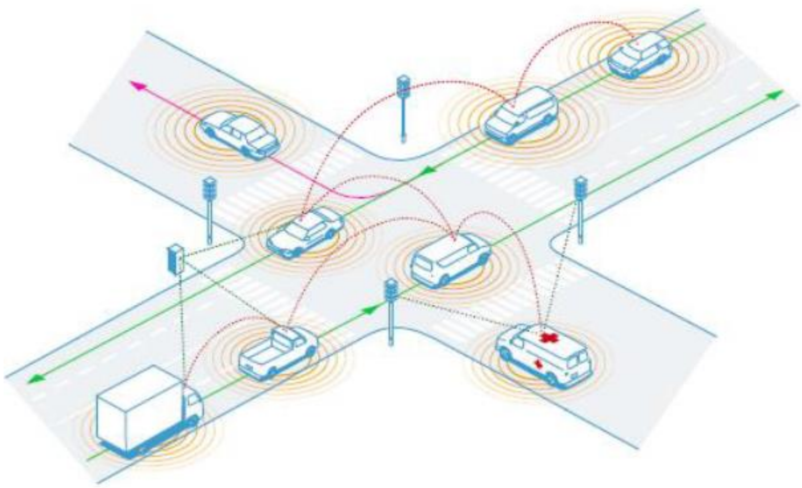


Figure 28. Virtual coupling of vehicles on the road - C-ITS network.
(illustration: https://sites.psu.edu/ist110pursel/2015/10/08/vehicle-to-vehicle-communication/)

7.2. Radio for communication

For virtual coupling of motor cars, two complementary radio systems can be distinguished, namely: cellular and WLAN. Both systems will be explored.

Cellular LTE-V2X

Cellular-V2X (C-V2X), as initially defined as LTE V2X in 3GPP Release 14, is designed to operate in several modes. It provides one solution for integrated V2V, V2I and V2P operation with V2N by leveraging existing cellular network infrastructure[5] [16]:

- Device-to-device is Vehicle-to-Vehicle (V2V), Vehicle-to-(Roadway) Infrastructure (V2I) and Vehicle-to-Pedestrian (V2P) direct communication without necessarily

[5] https://5gaa.org/5g-technology/c-v2x/

relying on network involvement for scheduling. This link relies on the PC5 interface specified by 3GPP for device-to-device operation;

- Device-to-cell tower is another communications link which enables network resources and scheduling and utilizes existing operator infrastructure. Device-to-cell tower communications constitute at least part of the V2I proposition and is important in end-to-end solutions;
- Device-to-network is the V2N solution using traditional cellular links to enable cloud services to be part and parcel of the end-to-end solution.

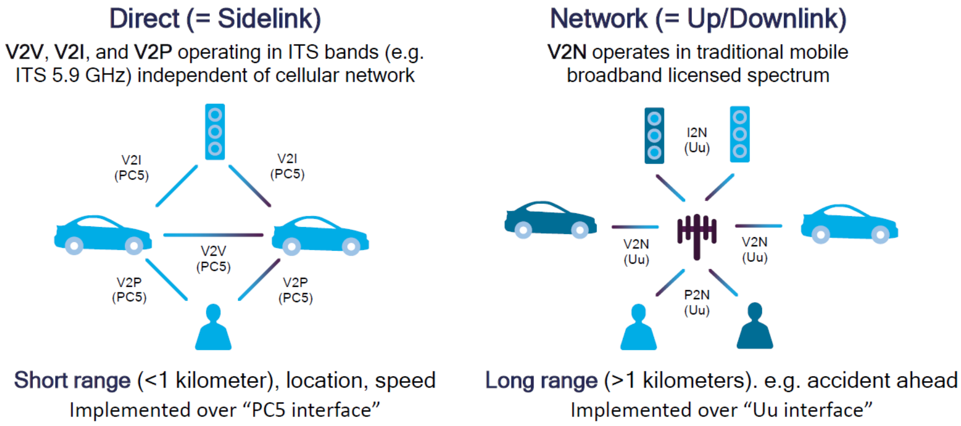


Figure 29. C-V2X has two complementary communication modes.
(illustration: Path towards 5G for the automotive sector Maxime Flament, CTO, 5GAA, 17 Oct 2018)

In the device-to-device mode (V2V, V2I, V2P) operation, C-V2X does not necessarily require any network infrastructure. It can operate without a SIM, without network assistance and uses GNSS as its primary source of time synchronisation. C-V2X also supports V2N applications utilising existing cellular networks where other voices and data communications occur. V2N would deliver network assistance and commercial services requiring the involvement of a Mobile Network Operator (MNO).

Collectively, the transmission modes of shorter-range direct communications (V2V, V2I, V2P) and longer-range network-based communications (V2N) comprise what we call Cellular-V2X Services. The current version of C-V2X is called LTE-V2X as part of 3GPP Rel-14 & 15

Cellular NR-V2X

5G NR (New Radio) is a new radio access technology (RAT) developed by 3GPP for the 5G (fifth generation) mobile network. NR is supposed to be the RAT beyond LTE and will come as an improvement to support autonomous driving. NR-V2X will complement and co-exist with LTE-V2X i.e. operation of NR-V2X alone was not considered.

W-LAN - IEEE 802.11p based ITS-G5

A critical element in Cellular LTE-V2X is that, seeing as it is: "subject to regional/national regulatory requirements and operator policies, certain mission critical services (e.g. Public Safety, MPS) can be relatively prioritized over transport of V2X application information. Transport of safety-related V2X application information can be prioritized over transport of non-safety-related V2X application information. However, in general, it is expected that operator can control relative priorities of different services".

It is this element that supports the case for a hybrid approach by combining Cellular LTE-V2X with ITS-G5 for non-latency tolerant use cases.

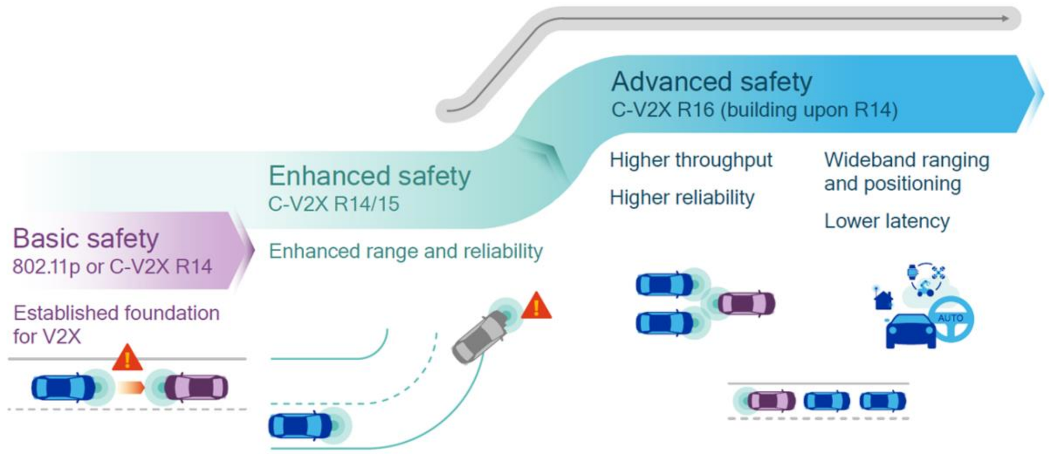


Figure 30. Co-existence of 802.11p based ITS-G5 and cellular LTE-V2X [16].

The CAR 2 CAR Communication Consortium members build their C-ITS deployment plans on short range communications via Vehicular Ad-hoc Network in the 5.9 GHz band, using the European and US market standards ETSI ITS-G5 and IEEE 802.11p. In comparison with other communication technologies, ITS-G5 displays some features well designed for safety-related applications: locally self-organising ad-hoc networks, free data transmission, robustness, independence of third-party commercial decisions and of communication networks.

7.3. 'Visuals' to scan the direct surroundings

A modern vehicle can contain a rich set of sensor technologies to scan the direct surroundings. i.e.: long-range radar, LIDAR, camera, short-range radar and ultrasound (Figure 31).

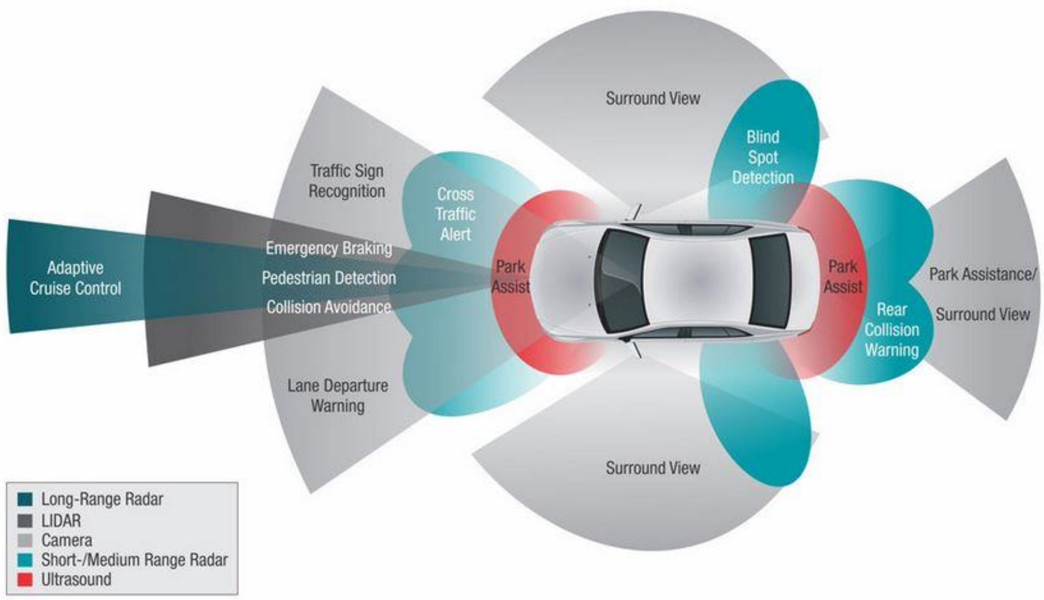


Figure 31. Sensor technologies to scan the direct surroundings of a vehicle[6].

[6] http://humancarinteraction.com/adas.html

7.4. Positioning and Localisation

Any V2X operation asks for high precision positioning for precise positioning, timing and velocity and heading estimation (Figure 32). Traditionally, the automotive industry combines the signals of multiple 'sensors' such as: Global Navigation Satellite System (GNSS), a gyroscope, an odometer and derived sensor using digital maps and map-matching of GNSS fixes. For navigation purposes this combination delivers sound results. For V2X higher levels are required for[7]:

- accuracy: the difference between the positioning system's measured and the real position, speed or time;
- integrity: the positioning system's capacity to provide a threshold of confidence and, in the event of an anomaly in the positioning data, an alarm;
- continuity: the positioning system's ability to function without interruption;
- availability: the percentage of time the positioning system's signal fulfils the above accuracy, integrity and continuity criteria.

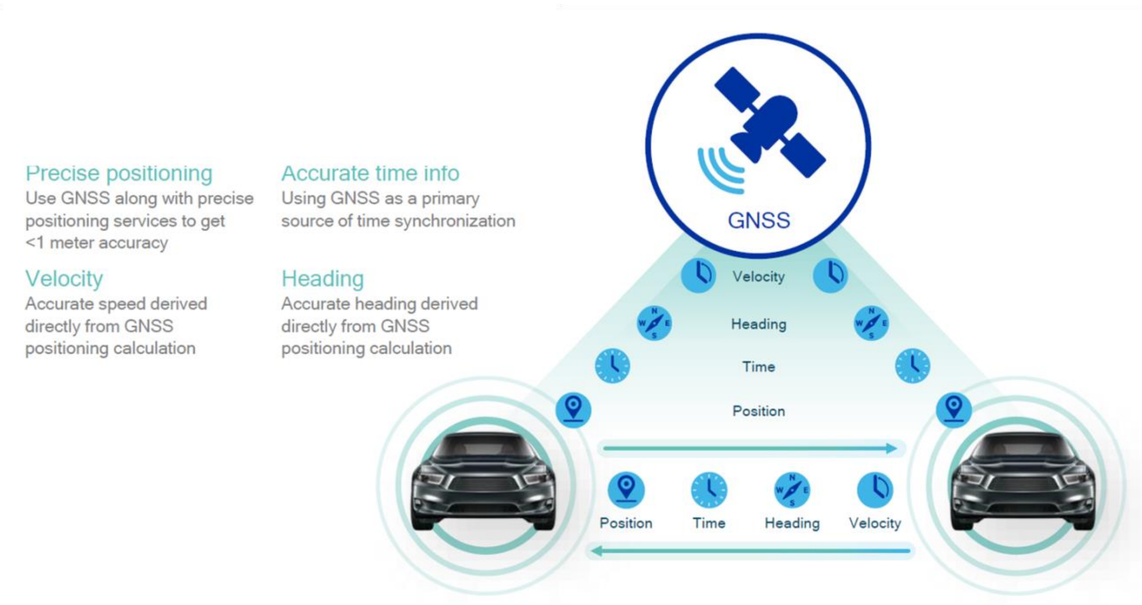


Figure 32. High precision positioning is key for V2X operation (and thus virtual coupling) [17].

Two developments are worthy of mention here, i.e.: high-precision positioning and high definition digital maps.

High-precision positioning

Correction data has long been key to high-precision GNSS services. Traditionally, a vehicle's positioning system device detects its approximate location and sends this information to its correction service provider. This provider uses a network of base stations to monitor GNSS errors, comparing the readings calculated from the satellite signals to the stations' known, fixed positions. It uses these insights to send the customer's device tailored correction data, based on its location[6].

The technology has successfully been used to provide centimetre-level accuracy in specialized markets. Restraining factors for scaling up to mass markets such as the automotive market are:

[7] https://www.gsa.europa.eu/european-gnss/what-gnss

- that traditional correction data services typically only operate in a defined area of a country and not all over the continent;
- that the pricing is far from what is acceptable in a mass market;
- the limited scalability, since the correction system requires beacons on the ground and two-way cellular communication in order to pass data back and forth between the customer device and the correction data provider. This comes with the risk that even safety-critical applications might lose access to the correction data service.

Another way to improve the positioning system's performance is to use regional satellite-based augmentation systems (SBAS), such as the European Geostationary Navigation Overlay Service (EGNOS). EGNOS improves the accuracy and reliability of GPS information by correcting signal measurement errors and by providing information about the integrity of its signals. Although highly relevant, SBAS (EGNOS) does not deliver the accuracy and reliability as required by V2X.

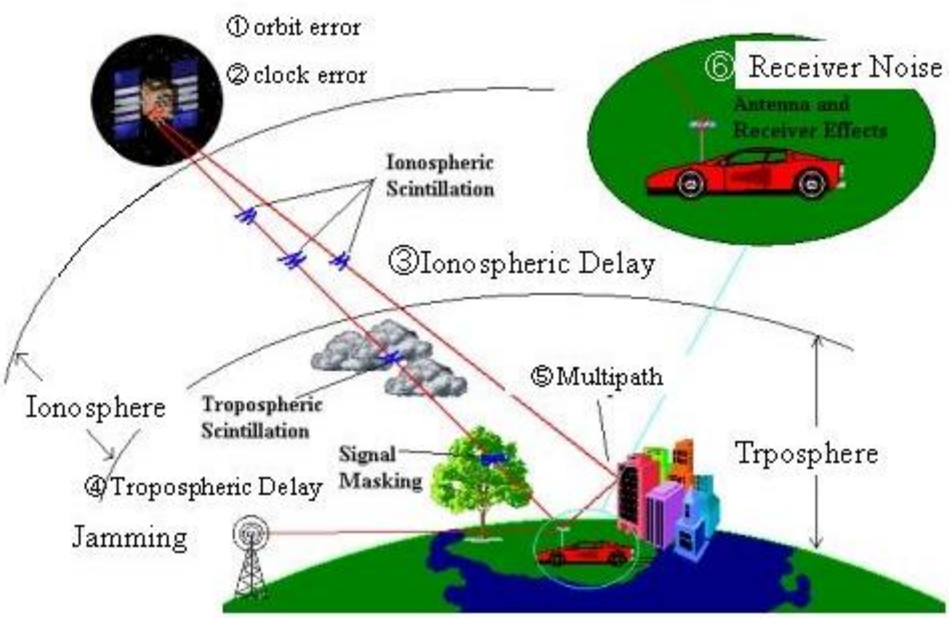


Figure 33. Illustration of errors in GNSS signals.
(Source: https://forum.xda-developers.com/showthread.php?t=1697306)

In the meantime, new a generation of GNSS correction services, creating and broadcasting a real-time model of relevant errors across their entire continent and also over satellite and/or the internet is in development. A new generation that comes with business models that promise to make high precision a mass market reality[8]. Technology using State Space Representation (SSR) is one form of these new generation GNSS correction data services.

High definition digital maps

Digital maps that are particularly built for automated vehicles are usually called High Definition Maps or HD Maps[9]. These maps specifically have extremely high precision at centimetre-level in three dimensions (3-D). After all, an automated vehicle needs to be able to level with a human driver in making decisions on roads. So far, the real-time decision-making capability, when it comes to driving and navigation is one of those key areas, where humans still have the edge. For

8 https://www.gpsworld.com/commentary-high-precision-positioning-is-going-mainstream/
9 https://www.geospatialworld.net/article/hd-maps-autonomous-vehicles/

example, decisions humans really take for granted such as stopping the vehicle in the right place, looking for a traffic signal at the intersection, or avoiding an obstacle in the road in a split second decision, are very hard for automated or autonomous vehicles to mimic. So, as part of the decision-making process, mapping becomes a critical component of helping the vehicles make the right decisions at the right time. Figure 34 is a good example of a 'noisy' environment that automated vehicles need to deal with.

Figure 34. 'Noisy' surroundings on the road.
(Source: Shutterstock, Markham, Ontario, Canada November 2015)

7.5. Security to gain trust in received messages

The C-ITS domain has specific features regarding security and privacy, which must be taken into consideration during the development of security solutions including cryptographic systems and Public Key Infrastructure (PKI). For Car 2 Car, for example, the following key challenges have been identified [10]:

- scalability. The security solutions must be scalable to support tens of millions of cars and trucks in each geopolitical area (e.g., Europe, Asia);
- heterogeneity of applications in the C-ITS domain. The security solution must be flexible to support various C-ITS applications both current and future;
- on-board end-point vulnerabilities. A malicious attacker may select to tamper with data (e.g., velocity, location, status of vehicle parts) of their source or the end-points of the wireless connection, rather than breaking the encryption of the connection itself.

Requirements for the provision and validation of the main security properties (availability, confidentiality, authentication, integrity, authorization and non-repudiation) depend heavily on the type of application supported by C-ITS. For example, depending on the type of information transmitted among the C-ITS nodes (e.g., C-ITS stations), the level of requested confidentiality can be higher or lower [18].

Some examples are given in Table 3 [19].

	Cooperative awareness (CAM)	Static local hazard warnings	Dynamic local hazard warnings	Area hazard warnings
Authentication and Authorization	Basic CAM authorization, Advanced CAM authorization Authorisation to claim priority rights for emergency vehicles Authorisation to state regulatory orders such as speed limits and road closures.	In general the requirements for Authorisation and Authentication are similar to CAM. In the subsequent unicast sessions, the local policies of the participating partners may require additional authorization and/or authentication.	In general the requirements for Authorization and Authentication are similar to CAM. In the subsequent unicast sessions, the local policies of the participating partners may require additional authorization and/or authentication.	Authorisation could be granted at several levels depending on the capabilities of the vehicle.
Confidentiality	CAMs are broadcasts to any possible receiver but some CAM messages can be still considered personal data and local data protection laws apply. Pseudonyms are used to protect privacy.	Depends on application and the related information to be exchanged	Depends on application and the related information to be exchanged.	No confidentiality services are required
Privacy	CAMs are sent periodically many times a second and pseudonyms are used to protect privacy.	As the nature of the service is broadcast and the sender is a static RSU, no confidentiality or privacy requirements apply	Depends on application and the related information to be exchanged.	No confidentiality services are required

Table 3. Some examples of security and privacy requirements for C-ITS messages [19].

The complexity comes from the restriction that any security infrastructure should also comply with requirements regarding the performance, organizational and processes point of view, such as [20]:

- time requirements for the signing and verification of messages;
- low latencies;
- simple processes for the distribution, installation, revocation of cryptographic material;
- flexibility of the security architecture and proposed solutions to support the appearance of new applications in the lifetime of the car. It is noted that a car's lifetime can usually range from 5 to 15 years;
- cost effectiveness. The price of the solutions cannot exceed the market constraints;
- harmonization at global level. Proprietary security solutions should be avoided, and global approaches should be supported to facilitate telematics and vehicle manufacturers.

Furthermore, the suggested security infrastructure should:

- not require the identity of the participating parties and, accordingly, support the goal of appropriately preserving privacy;
- be fast enough to fit within the bandwidth constraints of DSRC (5.9 GHz in Europe) and the processing constraints of the V2V on-board equipment;

- fit within the constraints of DSRC bandwidth and size of the BSM in the message payload; and
- support non-repudiation.

Note, that these requirements are only provided for informational purpose.

Last but not least, the security infrastructure should meet specific challenges for vehicular networks [21]:

- delay-sensitive applications. Many applications and especially safety applications in C-ITS are delay sensitive: messages must be transmitted, received and authenticated in a very short timeframe;
- scalability. The security solutions must be scalable to support tens of millions of cars and trucks in each geopolitical area (e.g. Europe, Asia);
- heterogeneity of applications in the C-ITS domain. The security solution must be flexible to support various C-ITS applications both current and future;
- On-board end-point vulnerabilities. A malicious attacker may select to tamper with data from their source or the end-points of the wireless connection rather than breaking the encryption of the connection itself.

It is this super positioning of requirements that makes security and privacy a challenge that is not easy to tackle.

7.6. Challenge 1. Diversity that follows on working with mass market building blocks

The world of automotive comes with an open, highly competitive mass market, where diversity in used technologies for the building blocks is a given and interoperability is the key to overcome this diversity. Any of the next generation technologies is explored and enhanced in various places in the world. In the end this results in various commercial implementations of the same technology that are not interoperable per se, which require full interoperability over the continent in order to reach V2X with all vehicles, road infrastructures and vulnerable road users.

So parallel to the development of a next generation technology, standardisation bodies are working on interoperability. It is also possible that a de-facto standard emerges from industrial or public-private collaboration.

7.7. Challenge 2. Artificial Intelligence and the cut back in deterministic systems behaviour

In a world of digitalisation, it can be envisaged that software will take a more dominant position in ADAS and in ADS. And as such, it can also be envisaged that in the future, algorithms bolstered by artificial intelligence (AI) and more specifically deep learning will be able to facilitate many other tasks associated with autonomous vehicles such as [22]:

- detection and classification of any road event with the highest accuracy in minimal time. AI can help the driver avoid obstacles and dangers, adjust to traffic signs, and

avoid pedestrians. The operation can be both passive and active. Passive means that no action is taken by the system, the decision and action are made by the driver using dedicated alarms. Active means bypassing the driver and have appropriate actions taken by he system. Examples being lane-departure warning (passive) and lane-centring using automatic steering (active);

- AI can also be used to monitor driver attention and awareness by detecting early signs of fatigue, dizziness, and driver distraction, again resulting in passive or active actions. It would be possible that a car's driving profile can be adapted to a 'momentary driver' status. The actions that can result include a driver alert and speed reduction up to a complete stop, when driving conditions requires it;
- different environmental conditions make some sensors more effective at particular moments. Trained AI neural networks will automatically adjust to the most useful sensor subset at that moment. This sensor 'fusion' then provides the best driving decisions possible, given all the information acquired from all mounted sensors on the vehicle;
- AI neural networks called CNNs (Convolutional Neural Networks) are also one of the key techniques used in 'Deep Learning'. They can easily classify conditions that were too complex to solve with classical computer-vision methods. In the past, road events like approaching a crossing junction was a complex mission that involved too many rules for classical computing techniques. These are now commonly solved using the training of neural networks.

Apart from the potential of AI in ADAS and in the end automated and autonomous vehicles, AI comes with a challenge. Nowadays, ADAS come with industry-wide quality standards, in vehicular safety systems (ISO 26262: 'Road vehicles – Functional safety'). ISO26262 establishes specific safety requirements to reduce road safety risks to acceptable levels, and manage and track those safety requirements to produce reasonable assurance. Assurance that is accomplished in the delivered ADAS-product.

With AI non-deterministic technologies enter the field of automotive safety engineering, which brings a new challenge on how to reconcile these technologies against the much more deterministic ISO 26262.

Just to give an example, random numbers have a specific role in machine learning (one of the AI-techniques). Moreover, machine learning algorithms make specific use of randomness[10]. such as:

1. Randomness in Data Collection
Trained with different data, machine learning algorithms will construct different models. It depends on the algorithm. How different a model is with different data is called the model variance (as in the bias-variance trade off). So, the data itself is a source of randomness. Randomness in the collection of the data.

2. Randomness in Observation Order
The order that the observations are exposed to the model affects internal decisions. Some algorithms are especially susceptible to this, like neural networks. It is good practice to randomly shuffle the training data before each training iteration. Even if your algorithm is not susceptible, it

[10] https://machinelearningmastery.com/randomness-in-machine-learning/

is the best practice.

3. Randomness in the Algorithm
Algorithms harness randomness. An algorithm may be initialized by a random state. Such as the initial weights in an artificial neural network. Votes that end in a draw (and other internal decisions) during training in a deterministic method may rely on randomness to resolve.

4. Randomness in Sampling
There may be too much data to reasonably work with. In which case, the 'developers' may work with a random subsample to train the model.

5. Randomness in Resampling
Developers sample when they evaluate an algorithm. They use techniques like splitting the data into a random training and test set or use k-fold cross validation that makes k random splits of the data. The result is an estimate of the performance of the model (and process used to create it) on unseen data.

A serious and open question is: how to embed this randomness in automotive safety engineering (see box 4)?

Automotive safety engineering comes with a structured approach that covers a predefined set of steps, amongst which are the following [23] [24]:

- an item (a particular automotive system product) is identified and its top- level system functional requirements are defined;
- a hazard analysis and risk assessment is conducted and a comprehensive set of hazardous events are identified for the item;
- an Automotive Safety Integrity Level (ASIL) is assigned to each hazardous event;
- a safety goal is determined for each hazardous event, inheriting the ASIL of the hazard;
- a vehicle level functional safety concept defines a system architecture to ensure the safety goals;
- safety goals are refined into lower-level safety requirements;
- 'safety requirements' are allocated to architectural components (subsystems, hardware components, software components);
- the architectural components are then developed and validated in accord with the allocated safety (and functional) requirements.

Box 4. Automotive safety engineering.

7.8. Challenge 3. Master the complexity of automated driving

The Automotive industry as set out an ambitious path from driver assistance to automation of driver tasks. As a result the complexity will grow in in number of sensors, number of actuators and algorithms in the in-vehicle platform. For driver assistance and automation of driver tasks a vehicle needs a rich set of:

- sensors, to be able to sense vehicle's current state and status, vehicle driver's state and workload, 360 degree sensing of vehicles vicinity and disruptions in the traffic flow on the (tactical) manoeuvring horizon;

- intelligent applications to be able to perceive like a human driver would perceive the vehicle state and status, vehicle's vicinity and traffic flow conditions, and tune the vehicle status to the vicinity and the traffic flow conditions and even conduct manoeuvres in traffic autonomously;
- actuators to be able to focus vehicle's light beams, intervene on speed, headway, acceleration and deceleration and manage vehicle controllers to conduct manoeuvres in traffic.

This path comes with the challenge to [28]:

- master the complexity of driver assistance and vehicle automation in: (both in system architecture, data processing and human interaction;
- integrate seamlessly in the in-vehicle platform:
  - the growing amount of functions within driver assistance;
  - next generations of elementary components;
  - next generations of sensors, processing units and actuators to enable new ADS functions;
- reduce the overall costs of components;
- reduce the development time of AD(A)S.

To cope with these challenges a three step approach is required, i.e. [28]:

- draft a new software & hardware architecture (to master complexity, enable seamless integration of new AD(A)S functions and to reduce overall costs of components),
- design and validate a novel design and more efficient development process for new AD(A)S functions that is enabled by a platform to reduce the development time of AD(A)S;
- design and validate a novel platform that enables the development process to reduce the development time of AD(A)S.

The idea behind this three step approach is that the architecture, design and development process are interlinked (Figure 35). New A(A)DS functions are designed within the existing software architecture and after having being developed added to the software architecture. The platform is there to enable this interlinked process.

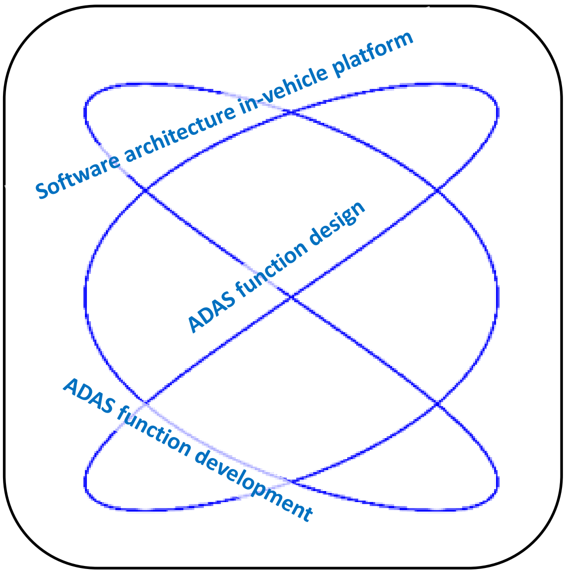


Figure 35. A novel design and development approach enabled by a novel platform [28].

7.9. Enabling technologies for roads versus railways

What can we learn from a high-level comparison between road and railways?

Continuous development of technologies

Rail traffic can piggy back on developments in automated car driving by
building on those developments, while preserving its own characteristics and specific requirements (Figure 36). 'Piggy backing' is of interest given that Automotive is a mass market, which brings pressure on costs. This answer does not bring a surprise, since most of these developments are already on their way.

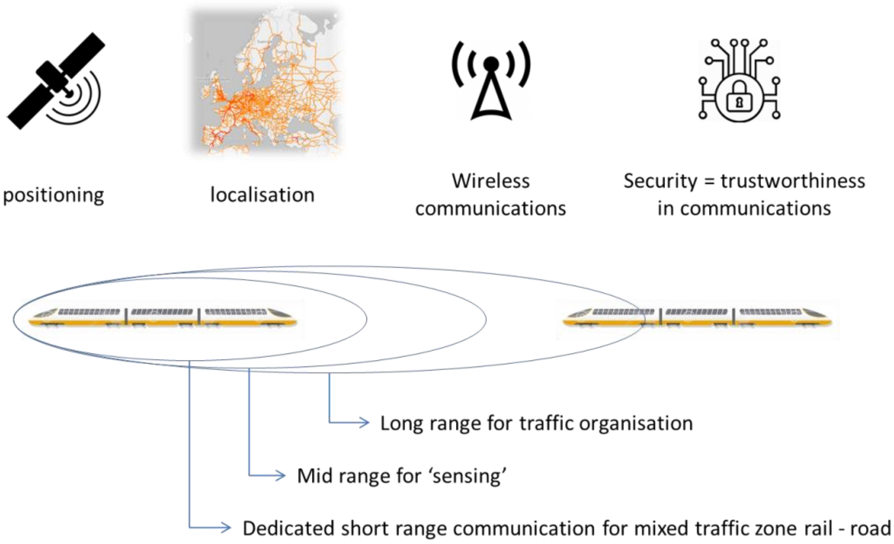


Figure 36. Rail traffic can piggy back on developments in automated car driving.

Artificial Intelligence and the cut back in deterministic systems behaviour

We live in a digital era where Artificial Intelligence (AI) will become ubiquitous. Now, in railways

(perhaps even more than on the road) stimuli will lead to a response, even if correct response is 'no action at this time'. As such, AI will impact fail-safe property of safety systems, which needs to be understood before rolled out. This is a serious challenge that needs to be studied.

In addition it is advised to study the impact on stochastics in behaviour in rail traffic that comes with the introduction of AI in safety systems in rail traffic.

8. Stochastics in traffic flow conditions

8.1. Diversity as a main characteristic of road traffic

One element of complexity of road traffic is in the openness of the system and the diversity within the system. This openness and diversity leads to stochastic behaviour in traffic and traffic flows.

Diversity in road surface

- type of road surface and road surface condition vary in the road network;
- type of road marking and road marking condition vary in the road network.

Diversity in road types

- crisscross traffic on roads with primarily an area function (in residential areas, at shopping centres, outside business premises);
- priorities ("which road corridor and/or which modality is more important above the other?") vary in the road network hierarchy and the function of the area (city centre versus trunk road);
- roads are characterised by disturbances (from residential area up to motorways with slip-on and slip-off roads, lane drops, "weaving" lanes, and so on).

Diversity in road users (mixed traffic)

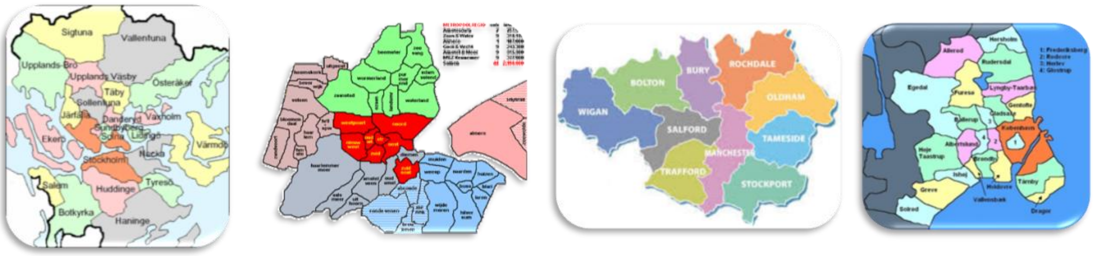
- mixed traffic on roads with primarily an area function;
- road user types power themselves differently and, as such, travel at different speeds and with various possibilities to react and come to a standstill over different distances;
- road user groups differ in maturity, experience and sense of responsibility.

Diversity in road surroundings

- surroundings of the road can be "noisy";
- on the roads vehicles are in between cluster (less dynamic) and swarm (highly dynamic) forming.

Political diversity

- Administrative borders turn road network into a jigsaw puzzles (Figure 37). Although high-level polices might be similar, every administration tends to detail out ('colour') these policies from their own perspective for their own area of responsibility. Altogether, the variety of policies in one (metropolitan) region might be counterproductive for traffic optimisation.



Stockholm Metropole | Amsterdam Metropole | Greater Manchester | Greater Copenhagen

Figure 37. Administrative borders turn road network into a jigsaw puzzles.

Diversity in countries

- speed limits;
- tolled roads;
- penetration rate of cycling;
- used techniques.

Diversity in traffic regulations

- traffic regulation varies in the road network depending on the surroundings, history of accidents, political arguments, and so on.

Diversity in vehicle types

- (de)acceleration levels and corresponding braking distances.

Diversity in driving behaviour

- Car (or more generic: road user) following style (Figure 38);
- Driver type (e.g. city-friendly driver, eco-friendly driver, comfort driver, sporty driver).

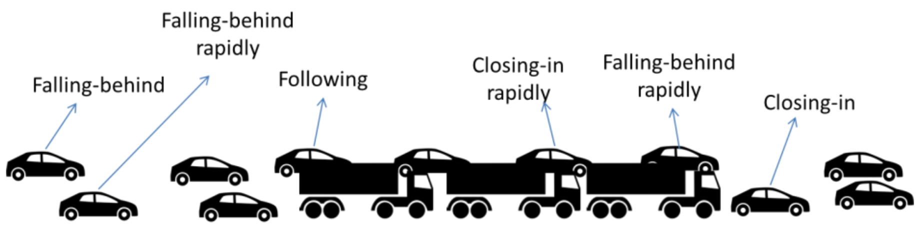


Figure 38. Illustration of the variety in driving styles.

8.2. Stochastic behaviour in road traffic flow conditions

Road traffic is always in a specific state that is characterised by the flow rate (q), the mean speed (u) and the density (k=q/u). We combine all the possible homogeneous and stationary traffic states in an equilibrium function that can be described graphically by three diagrams [8]. The equilibrium relations presented in this way, are better known under the name of fundamental diagrams. Figure 39 sketches them and it shows the relationship between each of the diagrams.

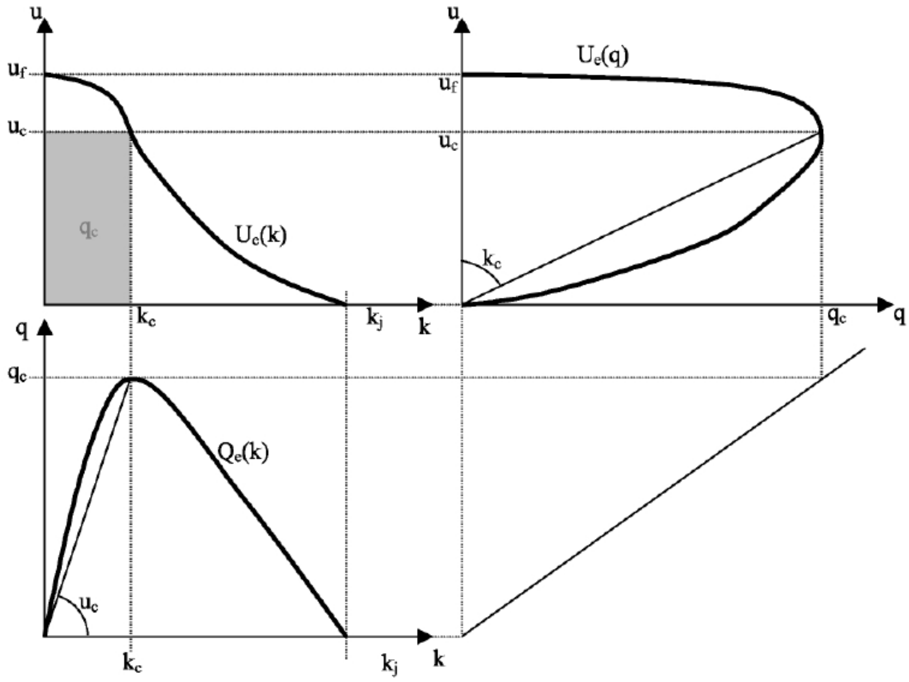


Figure 39. The three related fundamental diagrams for a motorway [16].

The stochastic element becomes visible at once when we step away from the theoretical diagrams and plot observations on a three-lane motorway of the measured flow rate q and the mean speed u during time intervals of one minute in a similar way. Each observation, now, gives an actual value for the mean speed u and a value for the flow rate q. Figure 40 shows the different observation points in a q-u diagram.

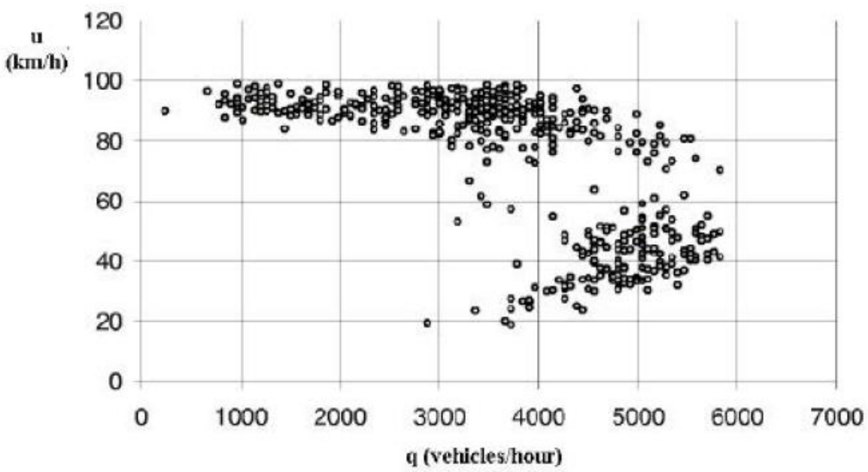


Figure 40. Observation points in a q-u diagram [8].

We calculate the density k (=q/u) for each observation. This means that the points of observation can also be plotted in a k-q diagram (Figure 8) and a k-u diagram (Figure 9).

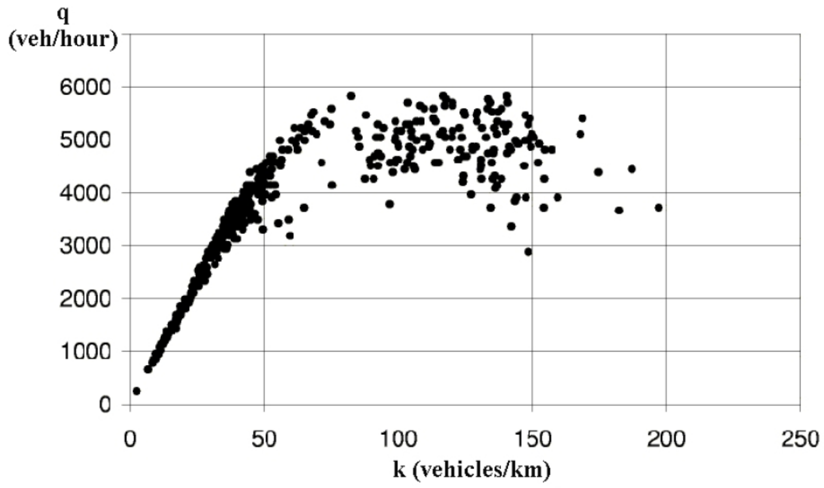


Figure 41. Observation points in a k-q diagram [8].

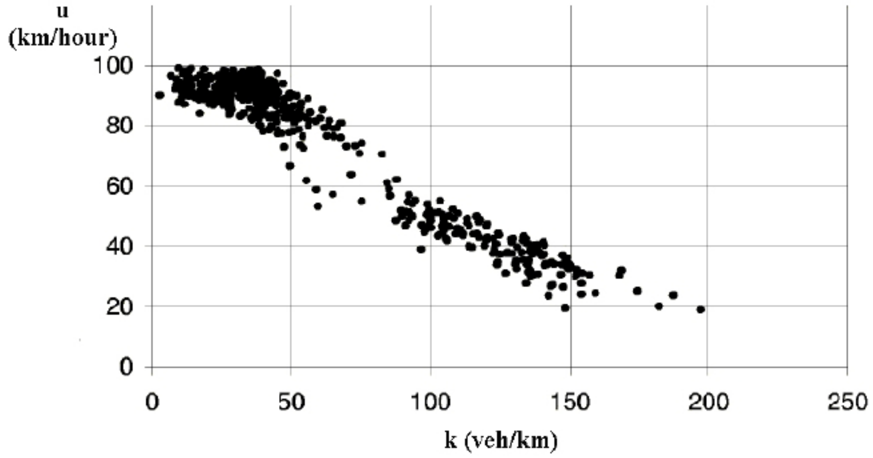


Figure 42. Observation points in a k-u diagram [8].

The observations were carried out on an actual motorway where traffic is not homogeneous: there is a variety of vehicle types and drivers behaving in a variety of ways. Nor is real traffic moving at a constant velocity: vehicles accelerate and decelerate continuously. Abstracting from the inhomogeneous and non-stationary characteristics, we can describe the empirical characteristics of traffic using an equilibrium relation that we can present in the form of the three diagrams shown above.

8.3. Stochastics in traffic flow condition on roads versus railways

What can we learn from a high-level comparison between roads and railways?

With moving blocks and virtual coupling and an intensified direct train-train and train – infrastructure interaction the stochastics in rail traffic flow might grow. It is worth the experiment in simulation models to see whether this assumption holds, and if so, how it can be counteracted to prevent a traffic flow breakdown. Breakdown is well-known to road traffic.

9. Conclusions (applicability to railways)

The applicability of applications, solutions and dynamics of automated car driving for railways is addressed in the paragraphs with which chapters 6 up to 10 are closed off.

The overall conclusion is that the steps in digitalisation of vehicles towards highly automated and perhaps even autonomous vehicles and the way this digitalisation is embedded in the overall traffic and transport management system on the road and in railways is a mutual source of inspiration:

- Railways can learn from the car centric approach on the road and the stochastics in the traffic flow that results from it. Road can learn from the way railways controls trains on its network.
- The road can learn from the strict safety culture in railways when it comes down on designing the enabling technologies and traffic control techniques. Railways can piggy back on developments in automated car driving, given that automotive is a mass market, which brings pressure on costs.

If we focus on the inspiration that railways can get from digitalisation of vehicles on the road, the following lessons have been drawn (following the analyses structure as presented at the end of chapter 3):

Automated driving

Where active safety on the road is rather vehicle centric, for railways it is a key responsibility of the infrastructure and rail traffic control system to provide safe passage, although more and more this is supported from equipment on the vehicles side. It might be interesting as an experiment in thinking to conduct a design exercise for railways with a strictly train centric approach to gain a better understanding of the possibilities and limitations of such an approach.

Cooperative intelligent traffic systems (C-ITS)

C-ITS can bring a value for ‘enhanced conspicuity’ in railways. Trains can warn, via C-ITS, cooperative road users that it is coming, while it approaches an unsupervised, level railway crossing. Trams (streetcars) can communicate its intentions via C-ITS directly with cooperative road users in its direct surrounding. This is the obvious usage of C-ITS for railways.

One step further, it might be interesting as an experiment in thinking to conduct a design exercise to embed C-ITS and cooperative driving (see Figure 14) in interlocking to gain a better understanding of the possibilities and limitations of such an approach.

Within the context of the designed and implemented timetables, it might be interesting as an experiment in thinking to conduct a design exercise to assess whether cooperative driving can help in aligning the driving speeds of individual trains dynamically to the current, mutual train position on the railway network and as such prevent stop&go manoeuvres and contribute to the energy consumption of trains. To some extent this already exists on the railways with Connected Driver Advisory Systems (C-DAS).

A last opportunity from C-ITS might lie in the interaction along platforms with travellers with the sole objective to come to an efficient process of alighting and subsequently entering the train carriages. C-ITS can help to spread travellers over the platform such that the concentrations of

travellers on the platform match the availability of empty seats places in the carriages of the train.

Interactive traffic management

The overall impression is that there is a high level of synergy between interactive road traffic management and the long-term aspirations of the emerging rail Traffic Management Systems (TMS). This impression needs a more in-depth analyses since the structures for interactive road traffic management on the road and in railways are in development.

Railways can also learn from the openness of road when it concerns traffic demand. The openness of railways is perhaps not so relevant to the traffic demand of trains, since the trains are fitted in an overall timetable. However, the openness of railways is strongly connected to the travellers that use the train as a crucial link in their journey from origin to destination. What railways might learn from interactive road traffic management is how to avoid the crowds on the platforms to grow to a size that can hardly or even not at all be handled by the train.

Enabling technologies

Rail traffic can piggy back on developments in automated car driving by building on those developments, while preserving its own characteristics and specific requirements. 'Piggy backing' is of interest given that Automotive is a mass market, which brings pressure on costs. This answer does not bring a surprise, since most of these developments are already on their way.

One emerging technology requires specific attention and that is Artificial Intelligence (AI). AI will become more and more ubiquitous. Now, in railways (perhaps even more than on the road) stimuli will lead to a response, even if correct response is 'no action at this time'. As such, AI will impact the fail-safe property of safety systems, which needs to be understood before rolled out. This is a serious challenge that needs to be studied.

Stochastics in traffic flow conditions

With moving blocks and virtual coupling and an intensified direct train-train and train – infrastructure interaction the stochastics in rail traffic flow might grow. It is worth the experiment in simulation models to see whether this assumption holds, and if so, how it can be counteracted to prevent a traffic flow breakdown. Breakdowns are well-known to road traffic.

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