DRIVING INTO THE FUTURE

Transportation evolution from autonomous driving to coordinated driving

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2018, updated in 2024

1 ABSTRACT

I present the actual status of the transportation evolution, focusing on the deliverables of key industries such as automotive, IT and telecommunication.

In the next 50 years, the main transportation evolution will be the shift of traffic management from individual vehicles to centralized solutions. Such a centralized application could unlock the potential of transport evolution for:
- Ultra-high level of safety
- Increase the speed of vehicles transporting people or goods from A to B.
- Shorter travelling time reduces the utilization of the existing roads.
- Reduce overall transportation's environmental impact.
- Provide prioritizations for all vehicles, thus enabling programmable transportation.

Autonomous vehicles are a must as soon as possible, but because they act independently, they might not be the most efficient solution for future transportation. But what if we could organize and coordinate them together? A three-step evolution path details the transition from individual autonomous vehicles to fully cooperative and coordinated vehicles.

New SW architectures must be implemented to support new centralized applications and telecommunication networks must be developed to provide proper connectivity and accessibility to vehicles and applications. The challenge is enormous for service providers to transform the existing brown-field networks into a future-proof network. The service provider's future role may be limited as other communication options emerge, like satellite, public networks, and short-range comms would be used.

I've prepared a high-level application design that includes traffic management policies, active/passive inventory, application instance management, and a traffic system application instance with a continuous situation engine and connectivity management.

Listing the required network capabilities of a central traffic management application based on 3GPP KPIs for transport use cases, including expected KPI values, new application hosting locations and resource management.

Critical telecommunication network development to support future transportation use cases and central traffic management applications:

➢ Connect mobile base stations to the application location with meshed architecture, ideally directly or via ring topology.

➢ Replacing actual physical and logical topologies with a more meshed topology to enable low latency and high mobility for applications.

➢ Enable application hosting at the access, backhaul, and backbone networks, but at least from the backhaul router locations towards the core sites. Roll out the required virtual infrastructure to these locations.

➢ Enable fast application session handovers among neighbour application locations.

➢ Implement mobile network resource orchestration to allow dynamic resource allocation per application requirements.

➢ Enable high upload speed up to 50-60Mpbs everywhere.

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2 The challenge: Traffic incidents

3.180 people died in traffic incidents on the roads in Germany in 2017. Another 390 thousand were injured, according to the *Bundesanstalt für Straßenwesen (BASt) [1]*. Suppose you look around Europe in the E28 countries. In that case, more than 25k people have died in traffic incidents in recent years, as reported *by the European Road Safety Observatory [2]*. To understand these numbers a little bit better, 390 thousand injured persons represent about 0,5% of the population of Germany every year. In a lifetime of 70 years, you have a 35% chance of getting injured in a traffic incident in Germany—statistically, one of every three persons closest to you.

Is it possible to save those lives, avoid those road casualties, or at least lower the number of accidents in the coming years? What is the contribution and responsibility of our Telecommunication Industry here? Could we, working in the Telecommunication Industry, support the design and build a solution to make traffic much safer?

3 What has been done until now to minimise traffic incidents? - Where is the industry today?

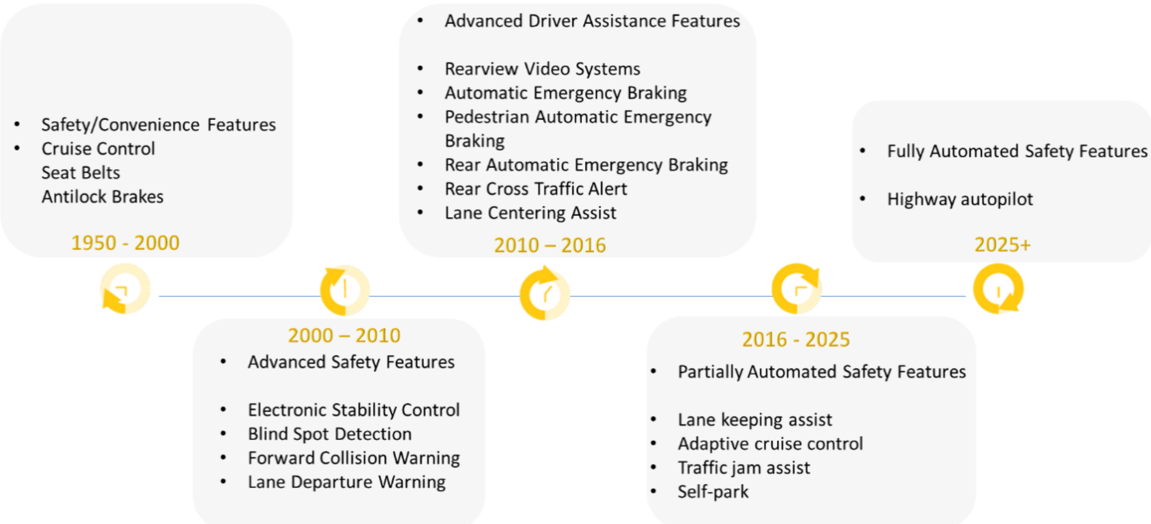
The Automotive, Telecommunication, and IT industries are the primary contributors to traffic safety improvements. The Automotive industry leads the related developments, and the Telecommunication and IT industries support them by providing the needed SW and connectivity solutions.

Until now, Automotive has contributed much more to the evolution of transportation safety than the IT or Telecommunications industries. During the last decades, assisted driving has brought many new safety features, like safety belts, ABS, etc. In recent years, autonomous driving has taken off by new intelligence and capabilities built into the vehicle. The Automotive Industry targets the highest possible safety level with autonomous vehicles' fully automated driving mode.

The IT sector is already contributing to the transport evolution by creating various SW solutions for vehicles; however, the Telecommunication Industry still needs to get up to full speed. Meanwhile, the standardisation work by the telecommunication standardisation bodies, like IEEE and 3GPP, is quite advanced, and many of these standards are based on automation use cases targeting increasing transportation efficiency; the Service Providers haven't rolled out the physical networks yet, which are required for such a new use case, like supporting ultra-low-latency, mobility, distributed application hosting and edge computing and others. Transport evolution is limited without the presence of proper network infrastructure.

3.1 A detailed look at the Automotive Industry

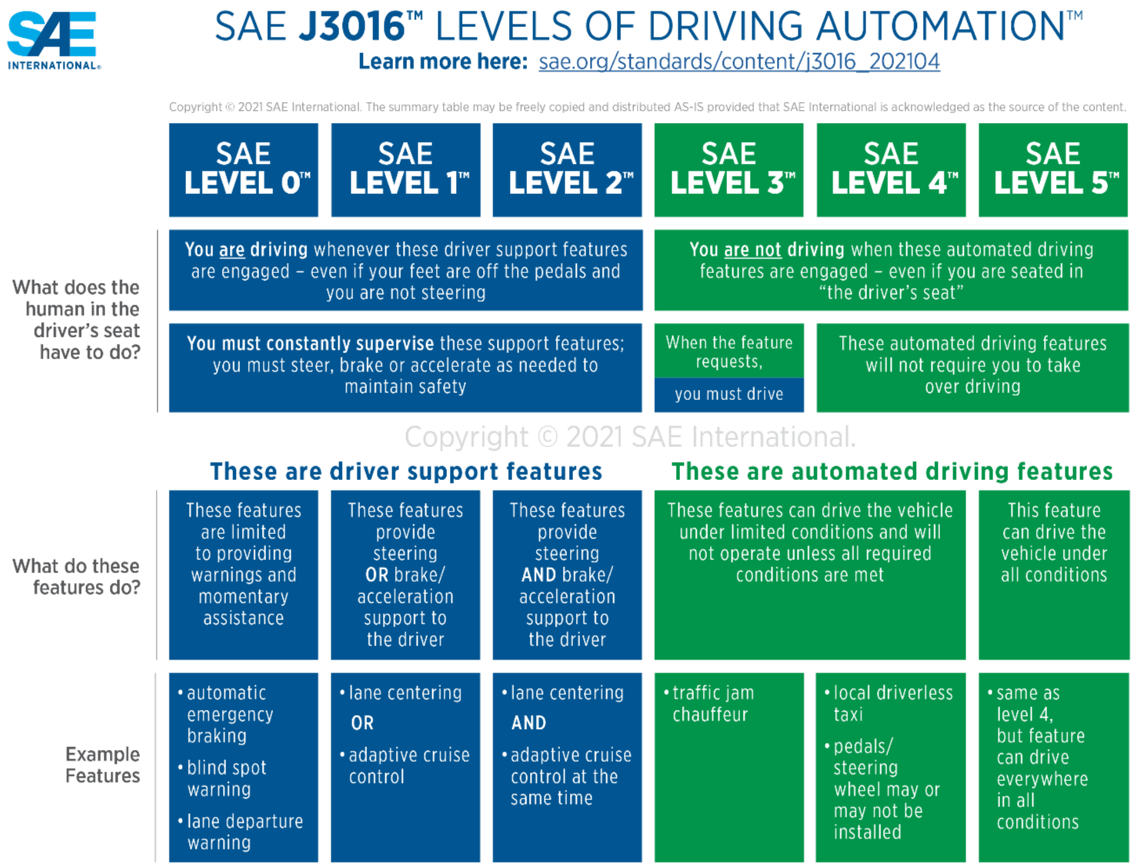
The Automotive industry has implemented many passive and active safety solutions in vehicles in recent decades. Advanced safety features of individual cars, such as blind-spot detection and collision warning systems, popped up around 20 years ago. In the last ten years, more driver assistance features and partially automated safety features, such as lane-keeping assists or adaptive cruise control, pedestrian recognition, automated emergency braking, etc, have become available in cars. Safety features are evolving towards full automation in the next decade. The following picture depicts the evolution path of the safety systems over 70 years.



Picture 1: Five Eras of Safety by NHTSA [3] shows the five main evolution periods from 1950.
Source: https://www.nhtsa.gov/technology-innovation/automated-vehicles-safety

Moving towards fully automated safety features might require more intelligent vehicles. Therefore, the path of safety improvements depends on the evolution of the vehicle's autonomy. The highest safety level might be reachable with fully autonomous vehicles that have self-driving capabilities. Future vehicles could drive alone in all conditions, without human interaction or even being monitored by a human being.

Enabling fully automated driving is a work in progress. Today, we might be on levels 2 and 3 of the SAE Levels of Driving Automation, as depicted in the table below. Most vehicles could automatically trigger specific actions, like emergency braking, but the driver must remain engaged. Some cars could run in autopilot mode, but the driver must take over the control at any time (like Tesla), and there are already some rare projects running in SEA level 4, like human driverless taxis started in San Fransico in 2023, https://waymo.com/waymo-one/.



Picture 2: SAE Levels of Driving Automation™ Refined for Clarity and International Audience
Source: https://www.sae.org/blog/sae-j3016-update

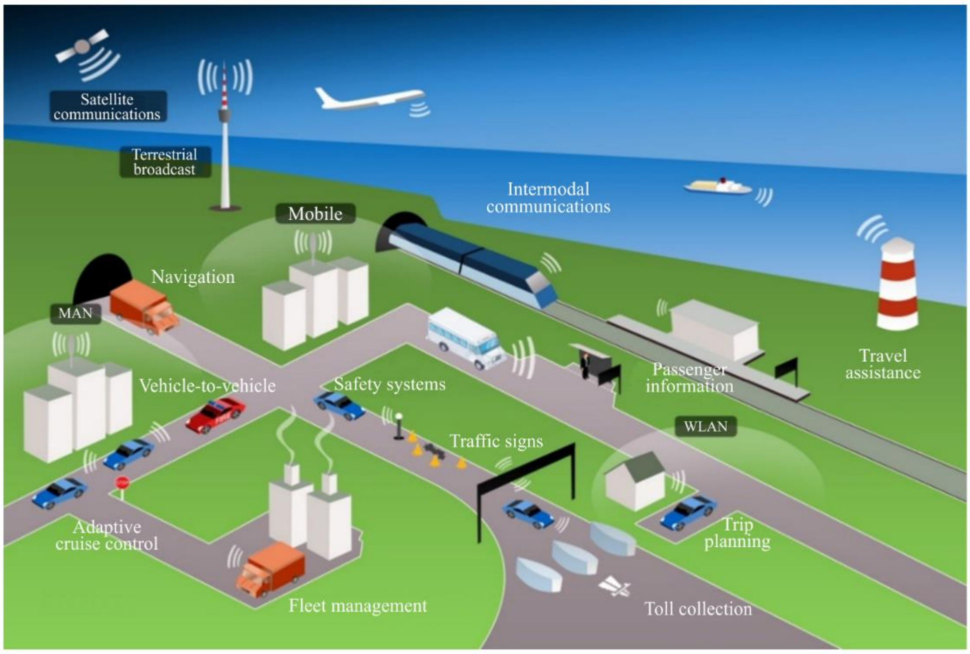
The date by which we could reach the last, complete automation phase is not yet clear. Tesla made some announcements some time ago, targeting the second half of 2020; however, some experts are less optimistic. [21]

Please refer to *Appendix 3* for a comparison of the safety levels of different transportation methods.

3.2 A detailed look into the Telecommunication and IT industries

Telecommunication and IT are the other two industries that contribute the most to traffic efficiency and safety improvements. They have delivered several solutions already. On the one hand, different SW solutions are used in the vehicles to extend their capabilities, like processing different sensor information, supporting assistance functions, etc. On the other hand, applications are developed outside the vehicles for various use cases, like route planning and map applications with dynamic content. Both internal and external-vehicle application development continues and will provide more use cases.

The Telecommunication Industry has already delivered the required standards to support different transportation use cases. These standards (by ETSI, IEEE, 3GPP, etc.) enable both short-range (<1km) communication (Dedicated Short-Range Communication, DSRC) and longer-range (>1km) communication (Vehicle to Everything, V2x).



Picture 3: ITU's Vision of the communication technologies and services for Intelligent Transport Systems.
Source: Intelligent transport systems (ITS) usage, Report ITU-R M.2445-0,
https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fwww.itu.int%2Fdms_pub%2Fitu-r%2Fopb%2Frep%2FR-REP-M.2445-2018-MSW-E.docx&wdOrigin=BROWSELINK

There are many places on the internet listing future transportation use cases. I recommend this 5GAA source for the first impressions, as it covers around 40 relevant use cases and provides a brief explanation of them: https://5gaa.org/content/uploads/2021/10/5GAA_Day1_and_adv_Use_Cases_Spectrum_Needs_Study_V2.0.pdf

3.3 Next steps and some more challenges

For the IT Industry, the most essential task is to keep delivering the desired SW solutions and cover more and more use cases. First, these solutions need to operate with the highest safety in different vehicles. Second, a SW release must operate across multiple vehicle types and generations. Consequently, backward compatibility of the SW will become a bigger and bigger task over time, as the same software needs to run on older hosting environments of different underlying HW.

Defining and developing a future-proof SW architecture is paramount and complex. On top of the usual SW architecture and development challenges, even more issues are raised for the existing automotive industry value chain, as highlighted by McKinsey. `...*As the Automotive Industry is transitioning from hardware- to software-defined vehicles... therefore one of the consequences is that premium automakers are moving into areas further down the stack, such as operating systems, hardware abstractions, and signal processing, to protect the essence of their technical distinction and differentiation...*`.
(source:https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/rethinking-car-software-and-electronics-architecture)

Below is the architecture referred to by McKinsey:

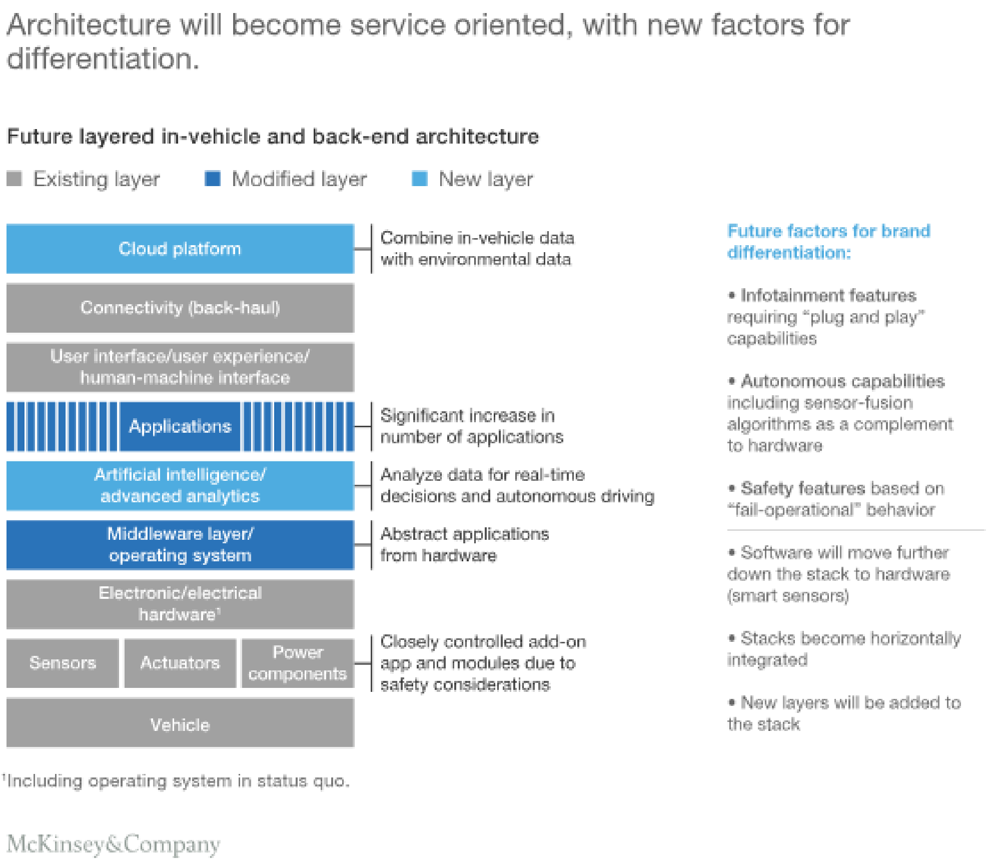


Figure 4: McKinsey: Driving Rethinking car software and electronics architecture.
Source: https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/rethinking-car-software-and-electronics-architecture

In parallel, the Telecommunication Industry might have two main steps to take. One step is to agree on a telecommunication solution on the industry level, as different technical options might be available for different use cases, like using DSRC or cellular networks. Such agreements among industry players will speed up the adoption of technology and rollout processes. Please refer to this article as an example of a comparison of different communication technologies: *Cook, Erin Lorelle: DSRC & 5G Comparison. Source: Why 5G may be the Ultimate Winner: A Comparison between 5G and DSRC.* [*https://erinlorelle.com/img/documents/5G.pdf*](https://erinlorelle.com/img/documents/5G.pdf).

The other important step is to upgrade the existing communication networks to enable the required network capabilities, like ultra-low latency, mobility, capacity, security, etc. The use cases with required network capabilities are defined across various 3GPP documents. For illustration purposes, I have copied the network requirements for the platooning use case here.

Table 7.2.2-1 Performance requirements for platooning

Communication scenario				Payload (Bytes)	Tx rate (Message/ Sec)	Max end-to-end latency (ms)	Reliability (%)	Data rate (Mbps)	Communication range (meters)
Section #	Description		CPR #						
5.1	Among a group of UEs (or two UEs) supporting V2X application		[CPR.P-004]	50-1200 (NOTE 1)	30	10			
			[CPR.P-005]	300-400	30	25	90		
5.2	Between UE supporting V2X application and RSU via another UE supporting V2X application		[CPR.P-006]	[50-1200]	2	500			
5.5	Between UEs supporting V2X application	Driver control	[CPR.P-007]	300-400 (NOTE 2)		25	90		
		Fully automated driving	[CPR.P-008]	1200		10	99.99		80
5.12, 5.13	Between UEs supporting V2X application	Conditionally automated driving	[CPR.P-009]	[6500]	50	[20]			[10] sec * (max. relative speed) [m/s]
		Highly/fully automated driving	[CPR.7.P-010]			[20]		[65]	[5] sec * (max. relative speed) [m/s]
5.12, 5.13	Between UE supporting V2X application and RSU	Conditionally automated driving	[CPR.7.P-011]	[6000]	50	[20]			[10] sec * (max. relative speed) [m/s]
		Highly /Fully automated driving	[CPR.7.P-012]			[20]		[50]	[5] sec * (max. relative speed) [m/s]

NOTE 1: This value does not including security related messages component.
NOTE 2: This value is applicable for both triggered and periodic transmission of data packets

Figure 5: Performance requirements for platooning. Source: 3GPP TR 22.886 V16.1.1. https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3108

The platooning use case demands a 10ms one-way latency between two user equipment over the cellular network and a 50-minute maximum network outage yearly. Service providers must invest heavily in their network to provide such capabilities everywhere or even more aggressive KPIs, like <5ms RTT with session continuity at 250km/h.

To further illustrate the future network demands, please find below a table from *A 5G Americas White* Paper with additional required network capabilities. Future telecommunication networks shall support all such use cases in parallel with their very different demands over one physical network.

Table 2.1 C-V2X service examples and recommended communication modes

Service Types	Example use cases	End-to-end latency (ms)	Reliability	Data rate	Recommended C-V2X mode
Safety	Cooperative Traffic Gap	50 ms	99.9%	2 Mbps	V2V
Safety	Interactive VRU crossing	100 ms	99.9%	64 Kbps	V2P
Vehicle Operation management	Software Update of Reconfigurable radio system	Delay tolerant (hours)	99%	200MB (delay tolerant)	V2N
Convenience	Automated Valet Parking (incl. authentication, proof of localization, wake up)	500 ms	99%	16 kbps	V2I
Convenience	Awareness confirmation	20 ms	99.9%	40 kbps	V2V, V2N
Convenience	Cooperative Curbside management	100 – 5000 ms	99.0%	Few kbps	V2P, V2I, V2N
Convenience	Cooperative Lateral Parking	10 – 100 ms	99.9%	27 Mbps	V2V
Convenience	In-vehicle entertainment	20 ms	99%	Up to 250 Mbps	V2N
Convenience	Obstructed view assist	50 ms	99%	5 Mbps	V2I, V2V
Autonomous Driving	Cooperative Lane merge	20 ms	99.9%	12 kbps	V2V
Autonomous Driving	Cooperative Maneuvers of AV for emergency situations	10 ms	95%	48 kbps	V2V
Autonomous Driving	Coordinated, cooperative driving maneuver	20 ms (each for 4 round trips)	99.9%	64 Mbps (system level)	V2V
Autonomous Driving	Vehicle Platoon in steady state	50 ms	99.0%	24 kbps	V2V
Autonomous Driving	Automated Intersection crossing	10 ms	99.9999%	~ 64 kbps	V2I
Autonomous Driving	HD Map Collecting and sharing	100 ms	99%	16 Mbps	V2N, V2I
Autonomous Driving	Infrastructure Assisted Environment perception	100 ms	99.99%	4 – 80 Mbps	V2I, V2N
Autonomous Driving	Infrastructure-based tele-operated driving	50 ms	99.999%	400 kbps	V2I, V2N
Autonomous Driving	Tele-operated Driving (ToD)	100 ms (UL); 20 ms (DL)	99.999%	36 Mbps (UL); 400 kbps (DL)	V2N
Autonomous Driving	Autonomous vehicle disengagement report	10 min	99.99%	26.7 Mbps	V2N
Traffic efficiency and society	Bus lane sharing request/revocation	200 ms	99%	40 kbps	V2I, V2N
Traffic efficiency and society	Continuous traffic flow via green light coordination	100 ms	95%	20 kbps	V2I, V2N
Traffic efficiency and society	Group start	10 ms	99.999%	20 kbps	V2I

Legend: V2I: Vehicle-to-Infrastructure, V2N: Vehicle-to-Network, V2P: Vehicle-to-Pedestrian, V2V: Vehicle-to-Vehicle

Figure 6: C-V2X service examples and recommended communication modes. Source: Vehicular connectivity: C-V2X & 5G. A 5G Americas White Paper
https://www.5gamericas.org/wp-content/uploads/2021/09/Vehicular-Connectivity-C-V2X-and-5G-InDesign-1.pdf

Service Providers face another challenge, too. Different industries play different roles in the intelligent transport ecosystem. Automotive Industry owns and drives the future of transportation services as it owns the most important part, the vehicle itself. Automotives will drive the overall transport evolution roadmap based on their industry's interest, creating uncertainty for other sectors, like Telecommunications. In addition, today, Automotive and SW developer companies can easily define and sell new products to customers and create new revenue streams. However, Service Providers don't have additional revenue from these new products because of the network neutrality principle and their own low success in moving into the over-the-top application space.

Another challenge for Service Providers might be their existing networks and the need to transform them into future networks. For more than 30 years, mobile networks were designed and built to deliver increasing capacity. Networks are still not capable of supporting ultra-low application session continuity with 5ms latency at 200km/h speed during a 300 km-long trip.

Transformation of the existing networks requires huge additional investments by an industry that is probably already operating with the highest capital demand level among the different industries.

Please find two graphs below to illustrate Service Providers' capital demand challenge.

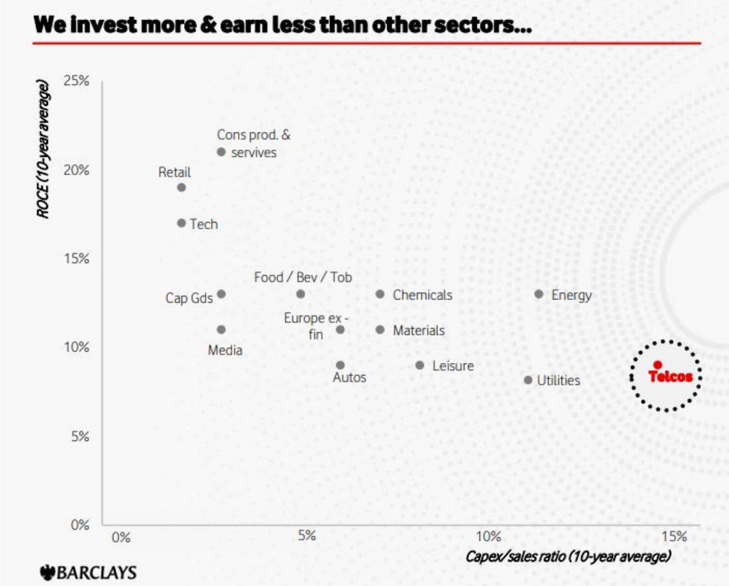


Figure 7: Vodafone must change | The market context. Source: Vodafone Financial results and presentations, FY23 Results https://investors.vodafone.com/~/media/Files/V/Vodafone-IR/documents/performance/financial-results/2023/Vodafone-FY23-Results-Presentation-v1.pdf

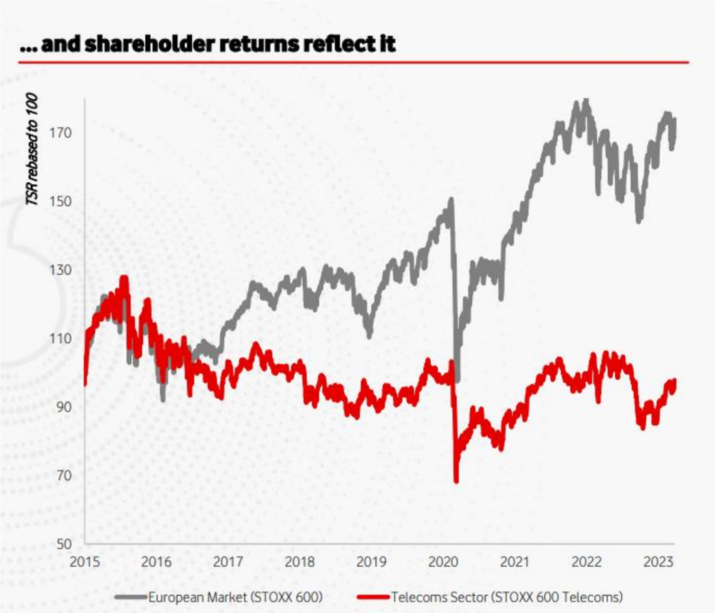


Figure 8: Vodafone must change | The market context. Source: Vodafone Financial results and presentations, FY23 Results https://investors.vodafone.com/~/media/Files/V/Vodafone-IR/documents/performance/financial-results/2023/Vodafone-FY23-Results-Presentation-v1.pdf

Considering all these challenges, would it be feasible to question whether the Telecommunication industry could offer any valuable solutions for the Automotive industry in time? Is the question *if* or *when*?

Could the DSRC or other solutions emerge as the preferred technology over cellular networks? Even 3GPP specifies use cases where vehicles are directly connected and using 5G technology but without using a mobile network *(LTE Direct protocol has been introduced in 3GPP Release 12 specification already. 5G direct protocol is detailed in Release 16 as well, e.g. as an option to connect the members of a platoon [4])*. What would the role of the Starlink satellites, having the same owner as Tesla, or the Helium initiative (*www.helium.com*) be in the future transportation ecosystems? Could they find a viable option of combining DSRC, public mobile networks and satellite-offered connectivity and building up a complete ecosystem of future transportation, including vehicles, traffic control applications, and communication infrastructure, without using traditional mobile networks?

Today, we tend to think that mobile service providers have already received their golden tickets because they cannot be dismissed from the value chain, even if they haven't found a monetisation model. But we might be wrong.

Anyway, we'll see in 7-10 years whether the service providers are catching up with delivering the required solutions on time with their mobile networks.

4 The need for autonomous vehicles and traffic management solutions

Autonomous vehicles have better reaction time than humans do. Machine drivers will deliver shorter stopping distances, contributing to higher traffic safety. Machine-driven cars could stop 10 meters earlier than humans from 50 km/h in dry road conditions. Please look at *APPENDIX 2 - STOPPING DISTANCES,* which demonstrates the different stopping distances of a human, a machine/self-driven, and various types of vehicles.

Autonomous vehicles are good at stopping distances; however, they are still autonomous in the sense of individually participating in the traffic. Therefore, one possible next question is: Could we combine their individual knowledge to build a shared, common knowledge? What additional use cases would be available by enabling such common knowledge?

As a baseline, autonomous and fully self-driven automated vehicles must be on the roads as soon as possible. More autonomous vehicles on the road could influence traffic safety and efficiency; however, as always, their technology adoption by the people is critical. Passengers, drivers, and the entire society need to accept the implied changes in transportation.

Such a technology adoption might start with those types of transportation where people already use external services, like taxis, public transport, or car sharing. Higher coordination of individual demands of passengers and goods will increase overall transportation efficiency. Some would be willing to share a vehicle and compromise their privacy and time for the lower cost of the travel. Other users might demand total privacy along the way of transportation but are willing to use their vehicle in auto-pilot mode and coordinate with other vehicles. Hopefully, this will not happen in the far future. With the increasingly demonstrated benefits, fully automated driving will become the standard method of transportation.

Soon, transportation might be available above ground level; for example, capable drones can deliver goods and passengers. Do you remember the city in the 5th Element movie?

Picture 9: Transportation used a multi-layer grid, which must have been tightly controlled …

To increase transportation efficiency and safety, we might to consider to build a central traffic management capability beyond increasing the number of individual autonomous vehicles.

5 A possible development direction for increasing safety: shifting autonomous driving capabilities from individual vehicles to central applications

Before starting to discuss any possible transport evolution steps, let's try to define the success criteria for future transportation:

- Ultra-high level of safety - no more casualties on the roads.
- Increase the speed of vehicles to transport people or goods from A to B. Moving faster with ultra-high safety would result in less time spent travelling.
- The lowest sum of the durations of the individual trips does not necessarily mean that each trip would be the shortest possible, but the sum of the trips would require the shortest time.
- Shorter travelling time reduces the utilisation of the existing roads, which would reduce the need for new roads in the future.
- Reduce overall transportation's environmental impact with better traffic management by considering noise, pollution, and sustainability impacts.
- Provide prioritizations for all vehicles based on other parameters, like emergency services, public transportation or the number of passengers. Prioritisation would enable programmable transportation.

Let's look at the following example to apply some success criteria.

Just imagine the following situation: you are approaching a crowded city centre where limited free parking slots are available. Let's assume that you, like all other people, want to arrive in the city centre as soon as possible and spend as little time looking for free parking slots or queuing in traffic jams. Like other vehicles, your car can detect free parking slots on the streets by its sensors.

Without any coordination, the empty parking lots are on a first-come-first-served basis, leaving some happy and disappointed drivers. These drivers might arrive later and need to spend significant time finding the next empty lot at various distances from the city centre.

Suppose we want to increase the summary of the happiness level of all drivers, in other words, to improve the efficiency level of traffic management. In that case, we probably need to create a solution to coordinate all arriving cars. Some vehicles could take the free parking lots close to the city centre. In contrast, others are directly moved to parking lots at a more significant distance from the city centre and move the passengers, e.g., with - even adjusted - public transportation.

In today's scenario, all cars try individually to find the next free parking slot. There is no coordination among the cars, so vehicles fight with each other for the same free parking slots.

In a more advanced scenario, higher traffic efficiency could be achieved by enabling individual vehicles to communicate with each other. In this case, cars are connected and can share information about their locations and knowledge of the free parking slots detected by their sensors.

In this scenario, the vehicles are connected. They could share their knowledge on the parking slots, but the competition for free parking slots is still there. To avoid such competition, we need to define which fee parking slots and which cars need to park at a distance. But what does the decision process look like? And who is making the decision? Does any prioritisation exist based on pre-agreed criteria, e.g., the number of passengers? Which car should make decisions? More cars to share the decision-maker role? How can decision-making assignments be managed with the dynamics of the vehicles that might join or leave the scene?

In a more advanced scenario, the decision-making process of the individual vehicles is harmonised. Harmonisation means that all vehicles accept and respect a single decision-making authority, wherever it is.

By a low number of vehicles (probably less than 10) in a traffic situation (like competing for free slots), a decision-maker authority could be nominated by the vehicles themselves, based on, e.g. random dedication of one of the vehicles. However, in the case of many cars, the decision-making function needs to collect and process so much information, that a single vehicle's available computing power would not be sufficient anymore.

Therefore, the decision-making authority for managing many vehicles should be a centralised function outside of any vehicles.

A central decision-making authority, hosted in a central application, would apply the pre-defined and agreed decision logic for all vehicles in the given traffic system. A centralised function would process information received from different vehicles in parallel, and the decision logic could be easily changed or finetuned as it is centralised. Vehicles would be responsible for sharing information and executing the orders received from the central application, except for a dangerous situation or emergency detected by the vehicle itself.

Using the previous example, the parking slot allocation will be done centrally, resulting in the lowest possible sum of the individual travelling time based on the pre-agreed logic of the traffic system, e.g. applying the following priorities for taking the closest available parking slots: 1. Emergency vehicles, 2. Vehicles delivering disabled persons, 3. Public transportation or charter transportation with more passengers, 4. Vehicles with children, 5. Vehicles with elderly persons, 6. Any other vehicles. An attractive feature of a centralised traffic management solution is that it can be quickly and dynamically changed, e.g., during occasional public events or severe weather conditions.

Technology adoption is always crucial, especially in this case, as the efficiency level of the central traffic management solutions depends on the ratio of the managed vehicles. I assume this dependency between the ratio of managed vehicles and traffic management efficiency is more exponential than linear.

5.1 A generic 3-step evolution path for shifting autonomous driving capabilities from individual vehicles to central applications

The following picture depicts a possible process for shifting traffic management from autonomous driving to central applications.

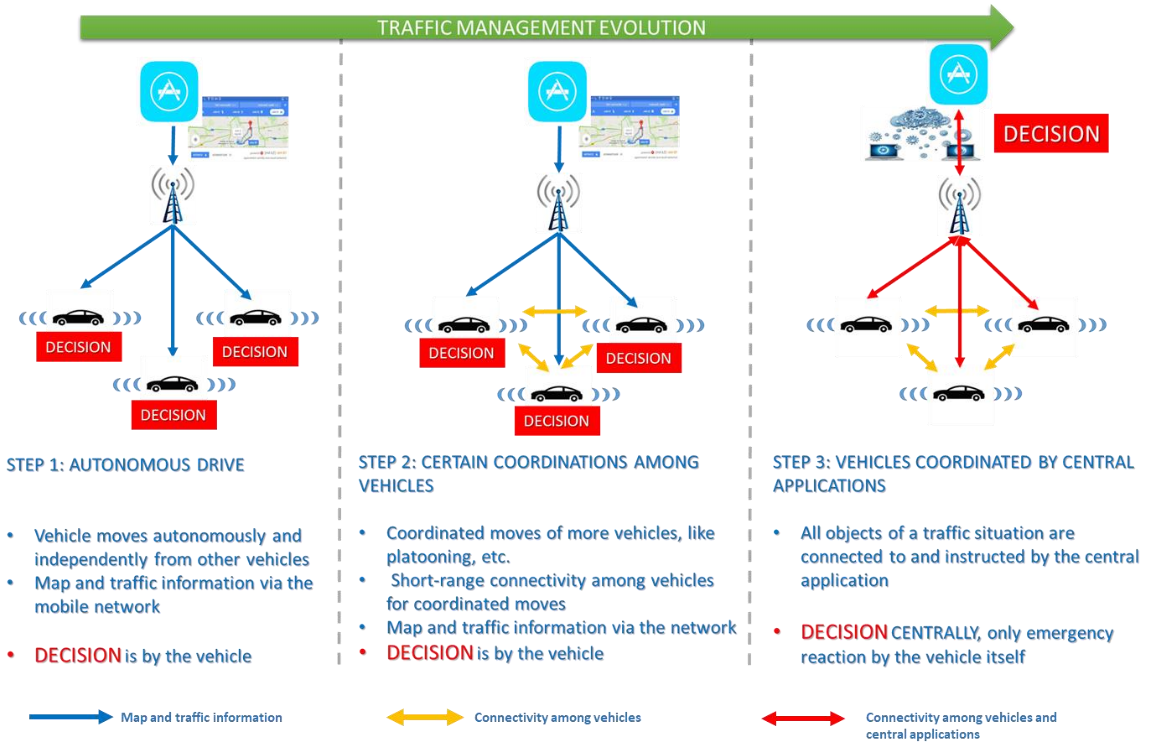


Figure 10: A 3-step evolution path of traffic management solution

In the ***STEP 1*** phase, the autonomous vehicles mainly rely on the information collected by their sensors. Vehicles are making decisions, like accelerating, braking, and turning autonomously. At this step, some information is used from external sources, mainly maps and relevant traffic information, jams, and roadblocks. *Local Dynamic Map provides [discussed in Appendix 1.]* an example of the evolution of the development and usage of traffic information. At this phase, vehicles are not connected.

STEP 2 introduces some level of coordination among a smaller group of vehicles on top of the capabilities of STEP 1. Vehicles are connected directly or via the mobile network and can perform coordinated movements (often called V2V). Such moves might be platooning (mounting and dismounting chain of a small group of vehicles), coordinated lane change, and other use cases. In STEP2, vehicles could share sensor and state information with others in the same group. *(Ref. [4] Specification # 22.886 - 3GPP, Study on enhancing 3GPP Support for 5G V2X Services. ' Chapter 5: Use Cases').* The decision is still with individual vehicles.

Connecting vehicles could support many use cases, like increasing the overall traffic density of the roads. For example, maintaining shorter gaps in a coordinated way among the vehicles might result in a two times higher traffic density, according to the study of *Impacts of Cooperative Adaptive Cruise Control on Freeway Traffic Flow* by *Steven E. Shladover, Dongyan Su, and Xiao-Yun Lu [28]*

STEP 3, described above, might support the highest safety level by managing all the objects together in a traffic situation. In this case, a central application controls all objects with engines, such as cars, trucks, buses, trams, and trains, and in parallel, considers all information for man-powered objects, such as pedestrians, bicycles, scooters, etc. STEP 3 might provide better benefits than STEP 2 by enabling new traffic management capabilities and better scalability by dynamically onboarding many more vehicles if needed. A central traffic management application could quickly scale horizontally to cover more parallel traffic situations. The application's vertical scalability enables use cases with various coverage, from collision detection between two vehicles to route optimisation across a wider geographical area.

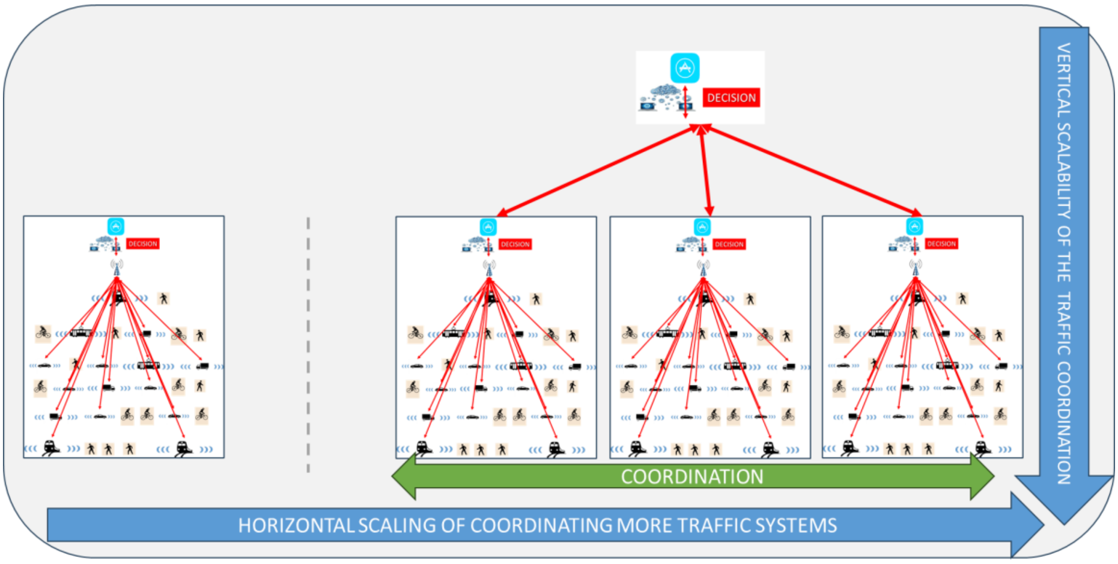


Figure 11: Vertical and horizontal scaling of the centralised traffic management solution

5.2 Do we need to shift the traffic control application to central locations?

Suppose we want to unlock all expected benefits of a central traffic control capability. One of the first tasks is to define the place of the application. Theoretically, we might be able to use the grid of vehicles itself to host the traffic control application. Let's have a look at this scenario. In this case, the application is distributed over many vehicles in the same traffic situation. Something like this:

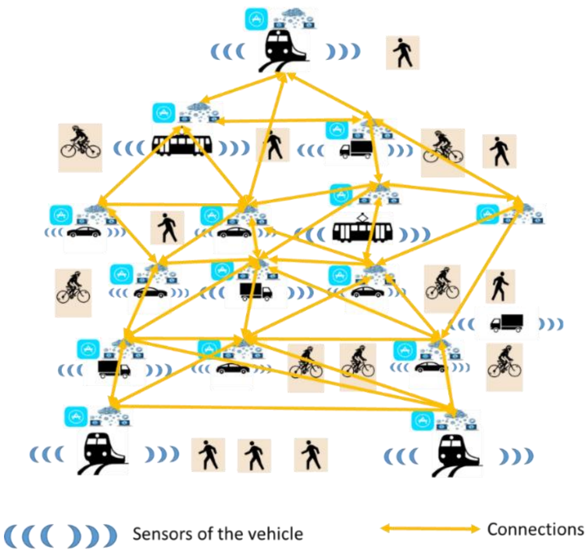


Figure 12 illustrates the needed connections among parts of the application hosting environment in the case of a distributed traffic management application.

Developing such a distributed architecture might present many challenges. One issue is creating a grid of the vehicles' resources as a hosting platform and managing connectivity among all the vehicles.

As vehicles can freely join or leave the traffic situation, the distributed computing environment provided by the vehicles changes frequently. Designing such a flexible infrastructure and application is very challenging.

Dynamically initiating or terminating connectivity among multiple vehicles could be difficult when a vehicle joins or leaves a traffic situation. Imagine a group of 5 vehicles, where ten connections would be enough to connect all vehicles. However, in the case of 10 vehicles, 45 connections are needed, and in the case of 100 vehicles, around 4950 links would be required to create a full mashed connection matrix.

The automotive industry runs initiatives and projects to exploit such a communication option for short and long-range vehicle connectivity. *(For example, the DSRC standard provides short-range direct communication of up to 1 km without any mobile network [29]*.)

Apart from the distributed hosting environment and the number of connections, the cooperative decision-making process of such a grid of vehicles would be another issue. As we have already seen by discussing our parking slots example, an ultimate decision authority must be selected and agreed upon. And we face a lot of questions immediately. How do we create the decision authority? Or do all vehicles have an equal vote during the decision-making process? And how do we agree on the rules which are followed by all cars? A cooperative decision may override the decisions vehicles would have made individually because of enforcing the common, agreed interest over the individual vehicles' interests.

Using a centralised application will be the most advanced scenario for providing not only the highest safety level but unlocking the highest number of further benefits, like reducing the time of travel or increasing the capacity of the roads, thus minimising the negative impact on the environment.

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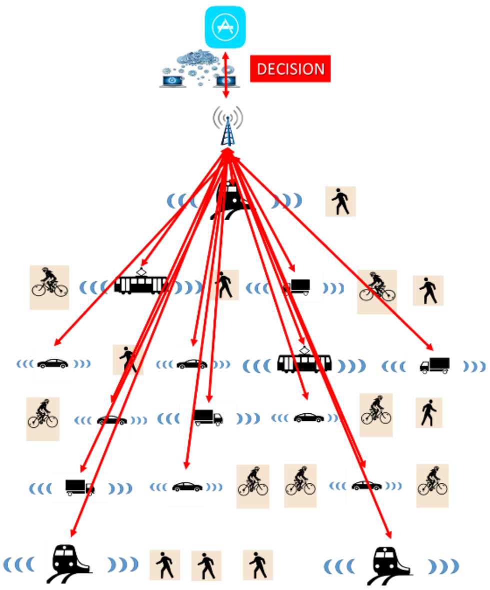


Figure 12 illustrates the connections needed in a central traffic management application.

With a central traffic management solution, the decision-making process becomes more straightforward because of clear roles and responsibilities. All vehicles receive instructions from a central application. A central application considers all active and passive objects (all engine and man-powered objects, roadblocks, etc.) that might impact a given traffic situation. The vehicles might compare the instructions of the central application to their independent judgments of the traffic situation, but they follow the central instructions. Again, vehicles would deny the received instructions only in case of emergency.

6 Designing the traffic management application – what to coordinate: the definition of the traffic situation/traffic system

The 'Roads in Germany' is a geographically abstract terminology; therefore, to initiate a tangible impact on the roads, we need to break down this term *into* physical traffic situations, including locations and objects whose safety depends on each other. As the first step, we break down the total traffic into individual traffic systems. A traffic system is the minimum traffic unit and contains all objects that can physically interact with each other. These objects could either cause an incident to another object or be harmed by other objects. Let's have a look into some parameters of a traffic system,

Traffic systems form and cease dynamically depending on the proximity of multiple objects. The number of such traffic systems and the number of objects in each system change dynamically and continuously.

Objects in a traffic system could be:
- moving objects, like cars, trucks, trams, trains, buses, bicycles, pedestrians even un-manned objects like balls passing the road or
- steady objects in the path of another moving object like parked cars, roadblocks, and holes on the road ahead.

Objects belong to the same traffic system if they can physically interact with other objects. The number of objects in a traffic system is a minimum of 2; the maximum number depends on the speed of the objects. That is because objects can reach different distances at various speeds. For example, an object moving on the road at 200km/h needs up to 150 meters to stop, which results in quite a significant physical area where it could interfere with other vehicles. At 10km/h speed, the object could stop at very short distances, resulting in a small physical area that could interfere with other vehicles.

Interaction happens in a traffic system when a vehicle is forced to change the speed and/or direction to avoid collisions because another object changes its speed or direction.

6.1 Examples of traffic systems

This section illustrates various traffic systems that could be formed individually or in parallel.

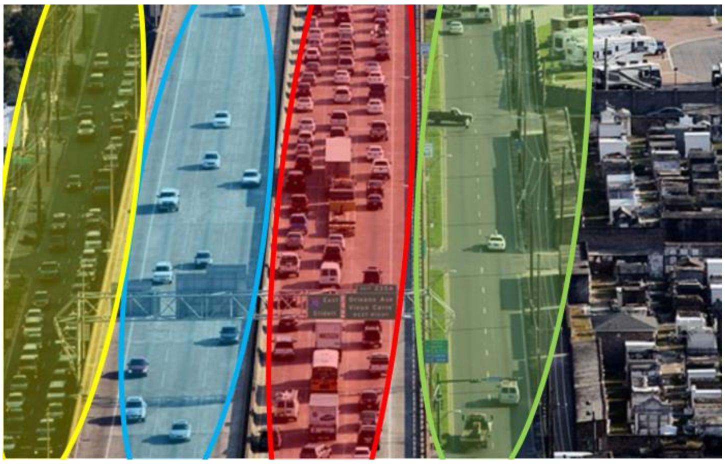


Figure 12. Four different traffic systems based on physical traffic isolation

In Figure 12, there are four different traffic flows. The various colours mark the objects belonging to a specific traffic system. The red and blue traffic systems have opposite directions on the bridge, physically separated from each other. The yellow and green traffic systems are on the ground level at both sides of the bridge, and each has one direction. They are physically separated and form the two other systems on the bridge.

Figure 13. One traffic system including different types of objects

In Figure 13, all marked red objects belong to the same traffic system. The tram, the bicycle, and the pedestrian are close enough to interact with each other, defining a traffic system of three different types of objects.

Figure 14. One traffic system with many different types of objects

All objects in the yellow area are in the same traffic system. Cars, pedestrians, bicycles on the pedestrian crossing, and motorbikes are in the same traffic system because they can physically interact.

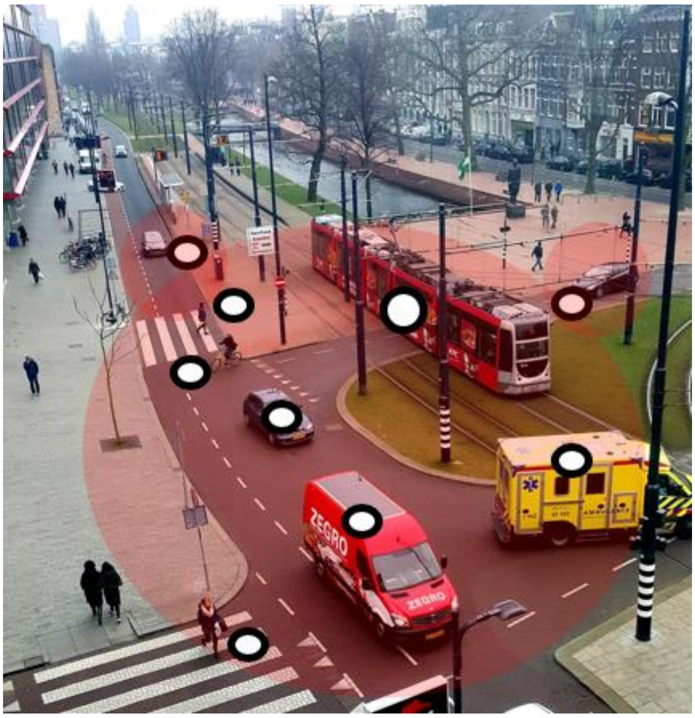


Figure 15: Some of the objects of a traffic situation belong to one specific traffic system, while others don't

Not all objects in this image belong to the same traffic system. Only those that are each other in the red area are three cars, two vans, a tram, a bicycle, a pedestrian at the crossing in the middle part, and another pedestrian crossing in the lower part of the picture. These moving objects belong to the same system. Other pedestrians and cars on the top of the image don't belong to this traffic system because their speed or directions could remain unchanged for extended periods regardless of the objects in the red area.

These examples above illustrate the general concept of defining a Traffic System. The exact parameters of a Traffic System might be fine-tuned for a real-life application.

6.2 The size of a traffic system

As we already defined, a traffic system needs to cover all the objects that could interact with each other. Therefore, the physical size of the traffic system depends on the distance a vehicle can reach in a given time. Specifying the 'in a given time' value might be subjective as different approaches could be applied. I chose to use the 5-second value for the 'in a given time' parameter because of similar references in some 3GPP use cases, and I couldn't justify any other better value to start with. The reference by 3GPP [4] for the use case is "*Information sharing for high/total automated driving. NOTE 3:In SAE Level 4 and Level 5 automation (cf. [23] [38]), the automated driving system is expected to be available for control without human intervention. To this end, the vehicle needs to obtain predictive information of environments sufficient ahead (e.g., [5] sec ahead). (cf. [24])* "

Another definition of 3GPP for information sharing for partial / conditional automated platooning use cases in the 3GPP specifications [4] is set at 5 seconds for the mobility scenario. It considers all objects that are at a 5-second distance from each other at any given speed. That means in the case of urban situations, where the maximum relative speed is 100 km/h (50km/h per direction), the size of a traffic system could be up to 139 meters. Whereas '… [278] m for the maximum relative speed of [200] km/h in suburban, and [347] m for the maximum relative speed of [250] km/h in Autobahn (same direction)….' [Specification # 22.886 - 3GPP, Page 33]

We could use the following simplified model to define the size of the traffic system (similar to the previous 3GPP reference above): a car takes around 14 meters in 1 sec at 50km/h speed, which is about 70 meters in 5 secs in the case of only one direction traffic. One traffic system should cover all vehicles in a chain until the first distance is more significant than 70 meters between two vehicles, one after the other. In the case of bi-directional traffic, the relative speed between cars is summing up to 140 meters.

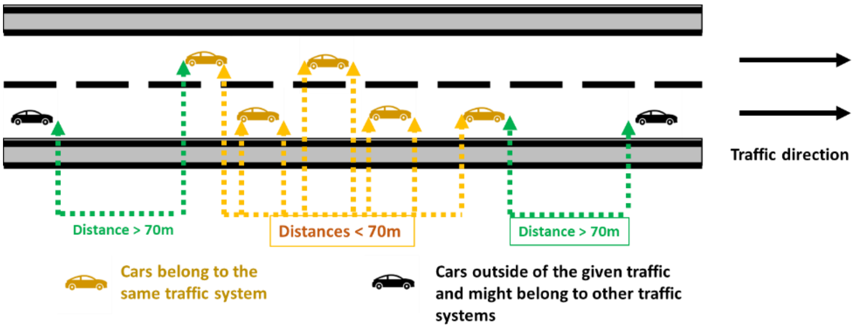


Figure 16: A Traffic system definition at 50km/h speed at dry weather conditions in case of unidirectional traffic

In this example, the five orange vehicles belong to the same traffic system, as the gap between two neighbour vehicles is lower than 70m in all cases (orange dotted arrows).

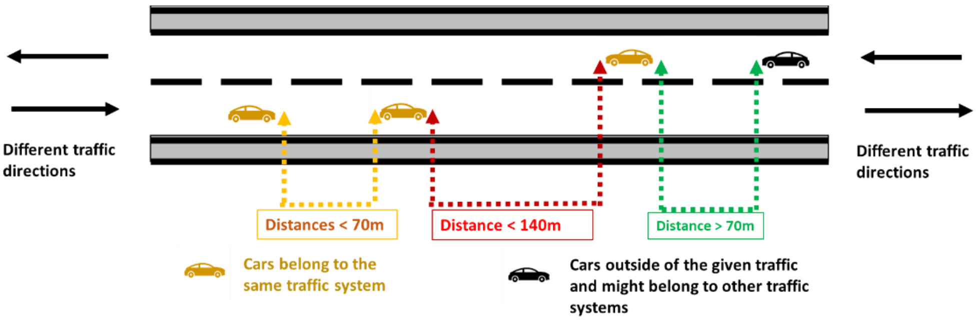


Figure 17: A Traffic system definition at 50km/h speed at dry weather conditions in case of bidirectional traffic

In this example, the three orange vehicles belong to the same traffic system, as either the gap between two neighbour vehicles heading in the same direction is lower than 70m (orange dotted arrows), or the gap between two neighbour vehicles heading in the opposite direction is lower than 140m (red dotted arrows).

Building a more advanced model, we shall consider the perception and reaction time of a human driver or a machine driver and the various stopping distances required for different vehicle types, such as motorbikes, cars, trucks, trams, and trains.

Please have a look at *APPENDIX 2 - STOPPING DISTANCES*, which demonstrates the different stopping distances for humans, machines, and self-driven vehicles.

The size of the traffic system is not static and changes dynamically according to road conditions, approaching vehicles, different vehicle types, and their actual speed.

7 Application High-level Solution design

This chapter describes the high-level functional design of a central traffic management application and highlights some critical technical requirements.

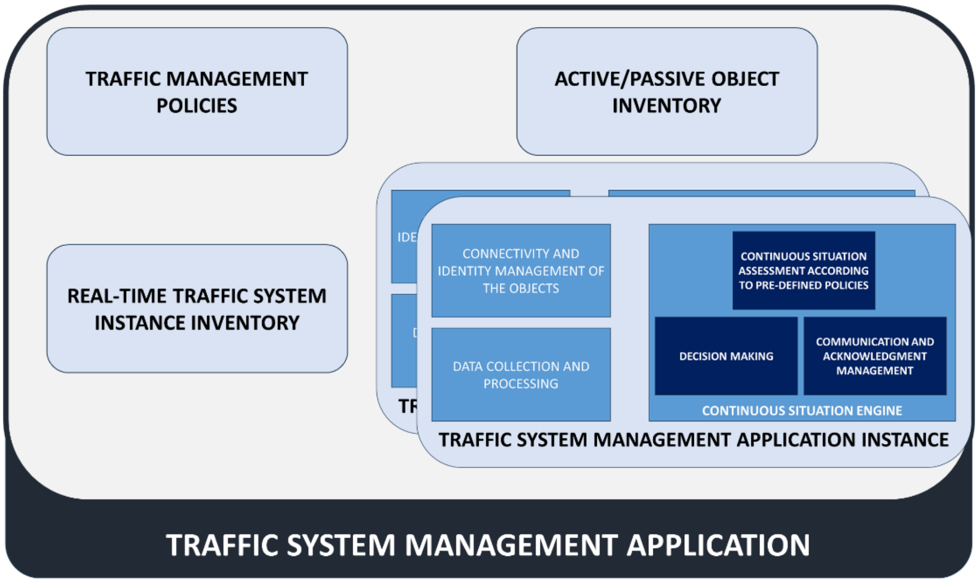


Figure 18: main components of the central Traffic system management application

The central traffic system management application has four main functions:

- The Traffic Management Policies function is responsible for creating, modifying, deleting and storing traffic policies with different associated enforcement levels. Policies with the highest enforcement levels contain the basic, general traffic rules, like general speed limits, right-hand rules, mandatory traffic lights, etc. Policies with the highest enforcement level are designed to be valid everywhere. Governance organizations shall be made accountable and responsible for managing these policies. Another set of policies with lower enforcement levels could temporarily amend the basic policies in smaller geographical areas. These additional policies could contain, for example, further speed limits, different priorities for different vehicle categories, creating temporary regions blocked from traffic, or even temporarily changing the direction of a one-way road or opening it as bidirectional. A third set of particular policies contains traffic improvement opportunities, like maximizing road density by increasing the speed of the vehicle beyond any speed limits defined in higher-level policies. Such policies are associated with the lowest enforcement level. Local Municipalities shall be responsible for building tailored traffic management policies for their geographical areas, like cities, villages and roads, by amending the basic, generic policies.

  Using traffic management policies allows us to define and implement our intent to represent how we would like to manage our traffic. Creating and enforcing those pre-defined intents enable traffic programmability.

- Active/passive object inventory: This function stores information on all known active and passive traffic objects, including their type, priority, and location.

Active objects collect and share information with the central application and can be controlled remotely, like vehicles and traffic signals; or collect and share information, but cannot be controlled remotely, such as objects like RSU (Road-Side Unit), pedestrians with handsets, or any man-powered vehicles. For the latter categories, the data collection and sharing might happen via mobile phones or similar devices.

Passive objects are not connected to the network and might not have any electrical components, like a hole in the road, a fallen tree, a human being without handsets or animals, etc. These objects are recognized by a connected object, like an engine or man-powered vehicle or by an RSU, which could share the location, size, and other information of such passive objects.

- The Real-time Traffic System instance inventory has two main functions. One function is to store information of the different live instances of the Traffic System management application in real-time, like covered geographical areas. When a vehicle starts its journey, one of its first steps is to check whether a valid traffic management system instance is effective on its location and send a request to the relevant instance to allow the vehicle to join. The other primary function is managing the communication flow among the parallel running instances and external applications. A Traffic System instance might share information from the covered area as such information could be helpful for the traffic efficiency in other areas covered by another traffic instance. A new roadblock or an emergency vehicle in one geographical area could trigger domino effects, causing traffic inefficiencies in different regions. Therefore, communication of such events to other traffic instances could support their efficiencies by updating their traffic management policies, similar to the *Replanning* functions of the existing navigation applications.

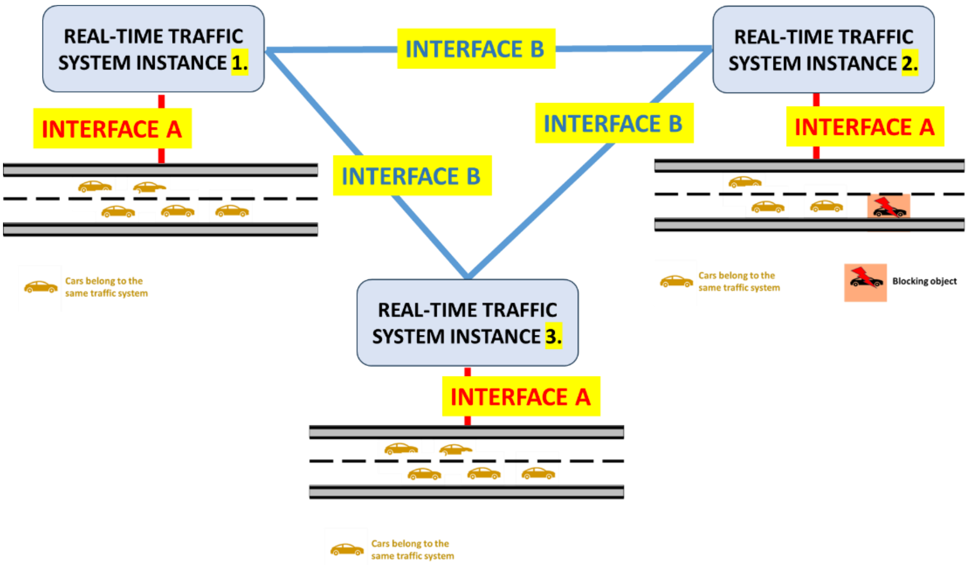


Figure 19: *Interface B* as a communication channel among different Traffic Management System Instances

The Real-time Traffic System instance inventory coordinates the relevant information exchange among different Traffic Management Application Instances on Interface B. The other interface, Interface A, depicts the communication between the application instance and its covered objects.

- A Traffic system management application instance is the core engine of the real-time centralized traffic management application, and one instance is created per one set of geographically dependent active and passive objects which could interfere with each other. An instance fulfils the following tasks:

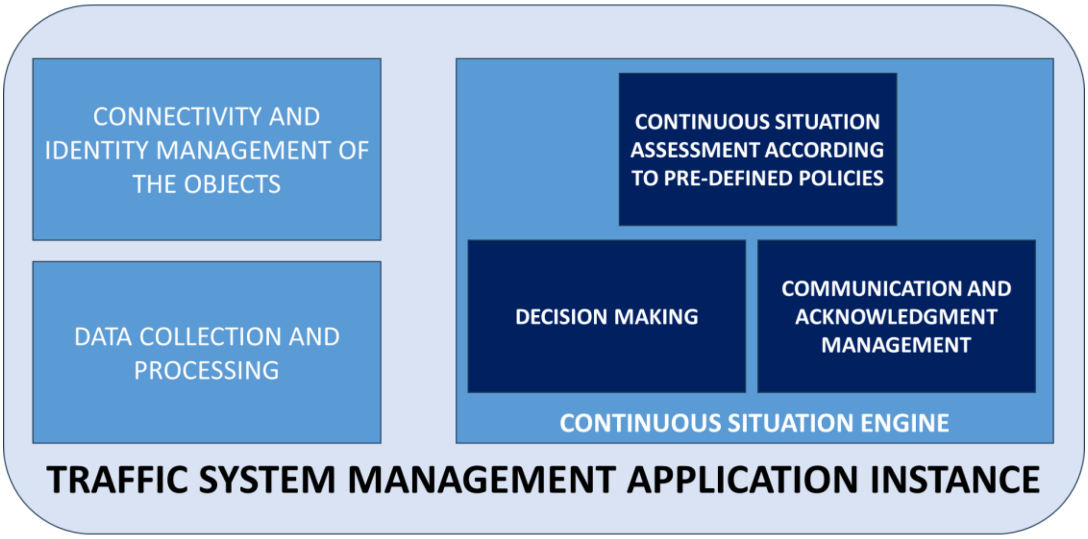


Figure 20: main components of a Traffic System Management Application Instance

- Connectivity and Identity Management of the objects*:* This function is responsible for the identifying, authentication and connectivity management of all active objects covered by one Traffic System Management Application Instance. Upon creation, it polls the Active/Passive Objects Inventory for a list of objects in the covered geographical area. It tries to establish connections and validate the parameters of those objects, such as object type, status information, autonomy level, and priority of the vehicle. This function negotiates the set of information that the active object can transmit, such as traffic signal information and sensor information from the RSU or the vehicle.

  Possible information types for active objects:

  - The most important information is the move itself: the position*, the speed, and the direction. Additional information is the condition of the vehicle, which would help to better predict the vehicle's reaction if the speed and direction of the move need to be suddenly changed because of a change in the traffic situation. Additional information could be the status of the tyres, brakes, engine, etc.
  - The other set of information collected by the vehicle is about the vehicle's surroundings. It is essential to collect and share the information gathered by a vehicle, like a roadblock or a hole on the road, because these passive – not connected - objects could not be seen by a central traffic control application in other ways.
  - RSUs could collect and share vast amounts of information, like traffic monitoring video streams. Different RSU types collect and share very different amounts of information.
  - Man-powered vehicles and pedestrians shall provide the necessary information about their moves via mobile phones or terminals. However, only limited information about their surroundings will most likely be collected.

  The successful operations of the Traffic System Management Application Instance heavily depend on identifying the proper information sources and the quality of the data collection process.

**The accuracy of positioning needs to be further improved. The standard GPS technology could provide the accuracy of approx. Of 10m in 2017, which would not be good enough for a traffic control solution. More location positioning technologies are available already and are improving continuously. The assumption is that even smaller handsets and terminals could reach the positioning accuracy of cm, possibly with the combination of multiple positioning technologies in the following years. 3GPP Release 16 contains the following demand for positioning: [CPR.G-007] The 3GPP system shall support relative lateral position accuracy of 0.1 m between UEs supporting V2X application.[4]*

- Data collection and processing function. This function processes the collected data into internal models to stream to the continuous situation engine.

- The continuous situation engine is responsible for continuously assessing the traffic situation by analysing the collected traffic information against the pre-defined policies in operation. The engine identifies possible policy violations, creates a snapshot of the traffic situation, and hands this snapshot over to the decision-making function. The engine then continues the traffic situation assessment.
  The decision-making function validates the policy violation and calculates the best option to prevent the policy violation. The calculated option contains one or more change orders in standalone mode for one object or a batch for multiple active objects. A change order shall request the change of speed and/or direction of an object.
  The communication and acknowledgement management function communicates the change to the traffic object and collects the object's response with the acceptance or rejection of the change order. An object shall not execute any central change order that puts the object at higher risk than the risk of the object's self-calculated option. If the traffic object accepts and executes the change order, the continuous situation engine updates the assessed traffic situation and continues the assessment.

8 Network capabilities supporting Application design

Designing an end-to-end traffic management solution requires considering both application and network capabilities. This chapter describes the required network capabilities supporting the central traffic management application described in the previous chapter. Such network capabilities must provide proper connectivity among vehicles (V2V), between vehicles and RSUs, and between vehicles and applications (V2x), enabling application hosting at the network edge.

Technical requirements will be detailed later in this chapter, but to provide a high-level view of such requirements early, please consider the following table:

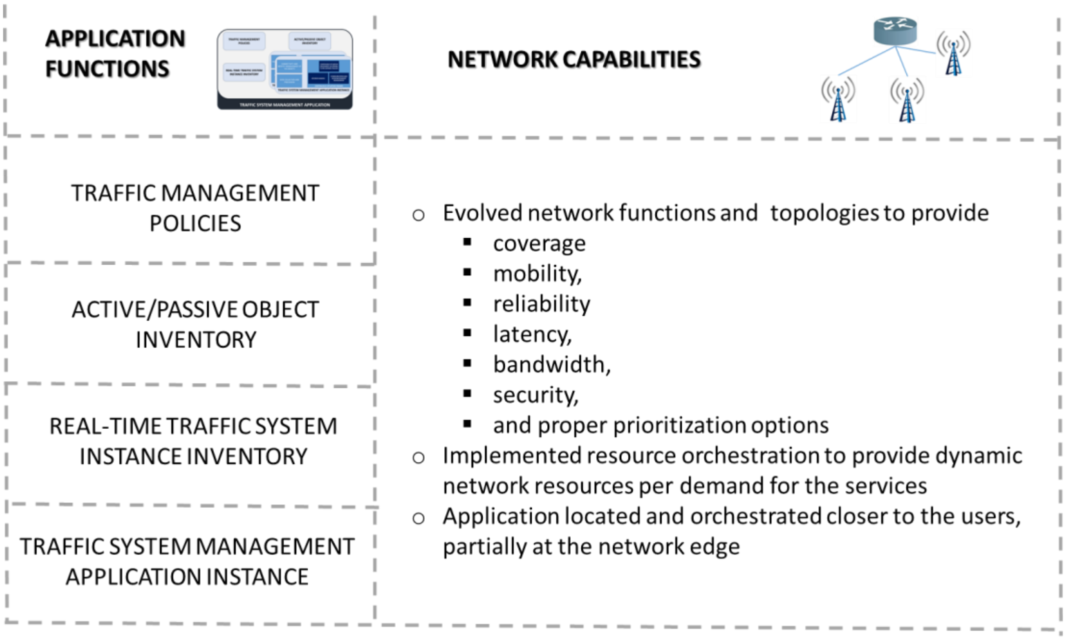


Figure 21: main network capabilities required for supporting the traffic management application's functions

Figure 21 lists the main network capabilities required for a central traffic management system. Standardization organizations, like 3GPP, have already defined such new capabilities across multiple technical specifications for supporting future transportation use cases (one example: *3GPP TR 22.886 V16.2.0 (2018-12) 3rd Generation Partnership Project; Technical Specification Group Services and System Aspects; Study on enhancement of 3GPP Support for 5G V2X Services (Release 16)* *https://www.3gpp.org/DynaReport/22886.htm [4]*).

Items listed under "Evolved network functions and topologies" are capabilities that must be enabled in future networks. These capabilities must support various KPIs, which will be detailed later in this chapter.

The second important network capability is the "Implemented resource orchestration to provide dynamic network resources per demand for the services". It refers to the ability to host and support different services in parallel on one shared physical network. Services could require a specific or a combination of multiple capabilities, like ultra-low-latency and/or ultra-high-bandwidth and/or session continuity at 250km/hour and/or 99,999% reliability. For network investment efficiency, network resources must be dynamically reserved and freed up per service requirements. The orchestration of dynamic resource management is critical to controlling the efficiency and cost of the network. (*Nb.: network slicing has been considered an option for transportation use cases. On the one hand, it could shrink the resource-*

allocation time for the newly instantiated services, as the resources are already reserved for the slice which this new service will use. However, slicing could result in wasting resources if the slice is over-dimensioned or there are more extended periods with lower utilization levels)

The third central network capability is the "Application located and orchestrated closer to the users, partially at the network edge" capability. It means that some of the application functions need to be located very close to the vehicles. Thus, some application instances need to be located at the network edge. On top of that, the application instance must be capable of being stretched or moved across multiple physical locations dynamically at the network edge. Such capability requires the orchestration of the application instances over the underlying virtual hosting environment. The application -, and virtual instance orchestration show similarities to the MEC (Mobile Edge Computing) orchestration and will most likely be implemented on a MEC-like infrastructure.

Figure 29 presents the demanded KPIs for different network capabilities, listed above as "Evolved network functions and topologies".

USE CASE GROUP	Max. e2e, one way latency (ms)	Reliability (%)	Data Rate (Mbps)
Vehicles Platooning enables the vehicles to dynamically form a platoon travelling together	10	99.99	65
Extended Sensors enables the exchange of raw or processed data gathered through local sensors or live video images among vehicles, road site units, devices' of pedestrian and V2X application servers	3	99.999	1000
Advanced driving enables semi-automated or full-automated driving	3	99.999	DL: 50 UL: 50
Remote Driving enables a remote driver or a V2X application to operate a remote vehicle for those passengers who cannot drive by themselves or remote vehicles located in dangerous environments	20	99.999	DL: 1 UL: 25

Figure 29: Main use case groups with the lowest latency, highest reliability and data rate requirements in 3GPP TR 22.886 V16.2.0 (2018-12). [4]

3GPP describes multiple use cases per use case group listed in Figure 29. KPI values present the strongest demanded values per a use case group. A fully operating central traffic management system, providing all use cases above, shall be supported by various network capabilities with their strongest associated KPI values. Therefore, actual network capabilities and outstanding network development tasks are referred to as the strongest KPI values.

The following table represents the use case demands in Figure 29 plus coverage, mobility and application requirements from the same 3GPP document, and matching them into a requirement table per network capabilities:

NETWORK CAPABILITIES	KEY NETWORK KPIS
COVERAGE	• Full coverage with the combination of different Radio bands or the UEs directly communicating to each-other
THROUGHPUT	• DOWNLINK up to 65Mbps and some use cases with 1Gbps. UPLINK Speed to ~50Mbps
LATENCY	• Latency down to 3ms among UEs and 5ms between UE and V2x applications
MOBILITY	• Up to 250km/h
RELIABILTY	• Up to 99.999%
APPLICATION LOCATION	• Application session is available throughout the route in stateful mode

Figure 22: KPI values per network capabilities based on the specifications in 3GPP TR 22.886 V16.2.0 (2018-12). *https://www.3gpp.org/DynaReport/22886.htm [4]*

9 Developing telecommunication networks

In the previous chapters, we drafted a possible high-level design for a centralized traffic management application and identified the network capabilities required to support such a centralized application. This chapter identifies the network development tasks to implement these capabilities. The next table describes the main network improvement tasks per key KPIs.

NETWORK CAPABILITIES	KEY NETWORK KPIS	KEY NETWORK DEVELOPMENT AREAS
COVERAGE	• Full coverage with the combination of different Radio bands or the UEs directly communicating to each-other	• Develop all existing and new RAN site locations to provide coverage
THROUGHPUT	• DOWNLINK up to 65Mbps and some use cases with 1Gbps. UPLINK Speed to ~50Mbps	• Increase DOWNLOAD speed up to 65Mpbs • Increase UPLINK Speed to 50Mbps
LATENCY	• Latency down to 3ms among UEs and 5ms between UE and V2x applications	• IP and Optical path optimization; • Distributed Data Core; • Application hosting environment
MOBILITY	• Up to 250km/h	• Session continuity at high speed and low latency
RELIABILTY	• Up to 99.999%	• Resource orchestration • MESHED Topology in Access networks
APPLICATION LOCATION	• Application session is available throughout the route in stateful mode	• Application hosting environment • Resource orchestration

Figure 23: Network development tasks to support the requested KPIs

Some network development tasks deliver more enabler capabilities, like implementing network resource orchestration or designing an application hosting environment at the network edge. Other development tasks target the implementation of specific capabilities, like reliability, coverage, throughput, or latency. The different development tasks shall run in parallel, but all of them must be completed to launch the central traffic management application.

9.1 Building up the proper network: Coverage

Coverage requirements cover two main aspects: the geographical coverage needed to provide connectivity for the user equipment and the number of concurrent equipment connected to the network.

9.1.1 Number of users' equipment

Many vehicles are already connected to a mobile network and authenticated by a SIM. It is a fair assumption that all engine-powered vehicles will be connected to a network over time. Man-powered vehicles, like bicycles, scooters, etc., may not all have integrated SIM cards in the future, but human drivers and pedestrians have them on their mobile phones. Mobile phones are there for connectivity and communication and can share location information as they move.

Let's define the connections required to support a centralized traffic system. Network connectivity would be required for all objects in a traffic situation, including all engine-based and man-powered vehicles and pedestrians. Let's assume that there are 0.7 engine-based vehicles per person on average. For comparison, in 2017, there were more than 57.5 million registered vehicles in Germany, with 45.8 million cars, 4.3 million motorcycles, and 3.1 million trucks and tractors [1]. Germany's population is 83 million. Man-powered vehicles like bicycles, scooters, and pedestrians must be connected to the network. This means one connectivity per person, but this is the as-is scenario already. The connectivity target is the sum of future connected objects, around 1.7 times the population.

Engine-based vehicles will demand the most new connections to a central traffic management solution distributed in the years following vehicle sales. For insight, 3.4 million cars were sold in Germany in 2018 [14], which indicates that it will take around 15-20 years to swap all the vehicles in the country. For comparison, the number of cellular IoT SIM cards in 2023 already reached 3.4 Billion Worldwide in 133 Service providers' networks and double the number of IoT SIMs to 6.7 Billion by 2029 (source: *Ericsson: Cellular IoT connections reached 3.4 billion in 2023. [33].*) Service providers could manage this additional connectivity requirement by the increasing number of connected vehicles in the following years.

The number of the maximum parallel connectivity could be referred to in the 3GPP document in section [CPR.G-009]. The 3GPP system shall support high connection density for congested traffic. An example of the estimate is for the worst-case US Freeway scenario that does not include arterial roads (i.e., onramps): 5 lanes in each direction or ten lanes total per highway, for up to 3 highways intersecting = around 3,100 to 4,300 cars per square kilometre.

9.1.2 Geographical coverage

For cellular connectivity, you need coverage and sufficient bandwidth to transmit data. The transmitted data volume depends on the available frequency ranges, not a specific frequency band. The more frequency you could use, the higher bandwidth you could achieve. The challenge is that an unlimited spectrum is not available. Please refer to the picture of the available spectrum in Germany below.

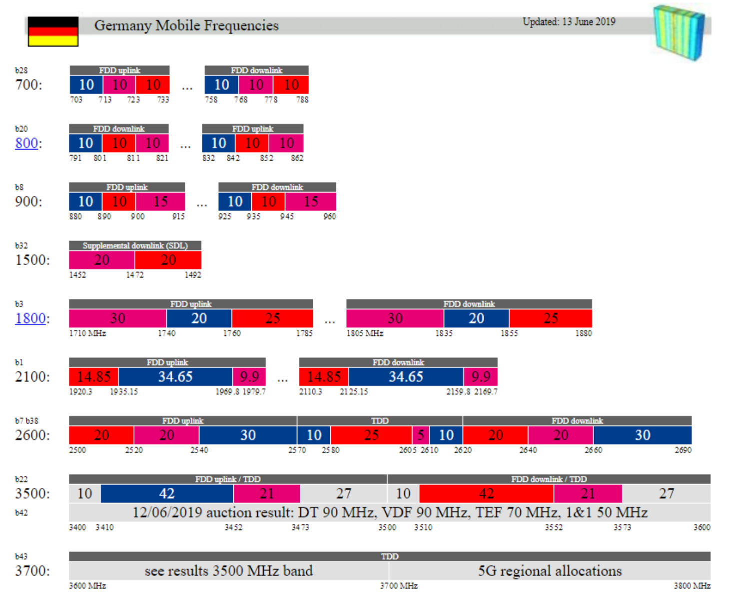


Figure 24: spectrum allocation in Germany. Source https://www.spectrummonitoring.com/frequencies/#Germany

Various frequency ranges are available in multiple frequency bands. In the 700MHz, the lowest available frequency band (from 703MHz to 788MHz) altogether, 60 MHz frequency is allocated for the Operators; in the highest 3,500 MHz (= 3.5 GHz) frequency band (from 3,400 MHz to 3,800 MHz), 300 MHz is made available for mobile service providers, and 100 MHz reserved regionally for enterprises for Mobile Private Networks. Indeed, a 10MHz range on the 700MHz band or 10MHz on the 3.5GHz band could transmit the same amount of traffic. However, the coverage areas are different. Lower frequency bands are better for addressing the coverage requirement because the propagation in lower frequencies is better. If you use higher frequency bands with more available frequencies, you must build more mobile base stations to cover the same area.

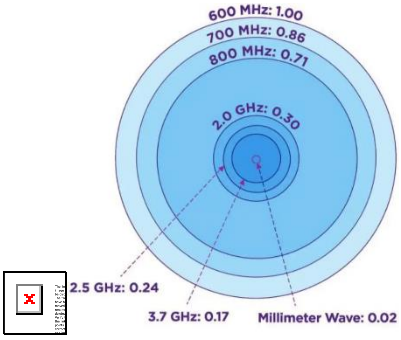


Figure 25: Cell Tower Coverage Radius with Low-, Mid-, and High-Band
Source: https://dgtlinfra.com/cell-tower-range-how-far-reach/ [13]

Based on the different sizes of the coverage areas, more than ten times more 2.6GHz sites would be needed than 700MHz sites for covering the same geographical area. Today, more than 99% of the population is covered by the Vodafone Network in Germany with 25,000 base stations, as per a post by former Vodafone Germany CEO. [16]. Base stations provide different throughputs in their coverage areas; the closer to the base stations, the higher the available throughput because of the additional available high-frequency bands. Even though the difference between geographical and population coverage definitions is known, there is minimal information regarding road coverage in Germany, except Interstate Highways *(“Autobahnen”*), which represent around 2% of the road system.

The German Road system consists of around 230.000 km of regional and around 400.000 km of local roads.

Straßenkategorie	**Deutschland** **Länge (in km)**
Autobahnen	13.192
Bundesstraßen / übrige Nationalstrassen	37.826
Landes- und Staatsstraßen / Kantonsstrassen	86.862
Kreisstraßen	91.841
Gemeindestraßen	398.000 (ca.)

Figure 26: Road types and lengths in Germany from the interstate Highways on top down to the community streets at the bottom.
Source: https://de.wikipedia.org/wiki/Stra%C3%9Fennetz [34]

Providing mobile coverage for all roads might or might not happen in the next decades. However, mobile coverage shall be rolled out from the highest-used to the lowest-used roads. Meanwhile, vehicles might be supported through the mobile network before they enter a low-coverage area, like downloading more detailed information about the non-covered area or information from moving objects that could potentially intersect the vehicle's movement. Even vehicles might increase the performance of their sensors, like temporarily increasing their radars' coverage area.

9.2 Building up the proper network: *Throughput*

3GPP documents define the throughput targets for Mobile networks. According to the 3GPP TR 22.886 V16.2.0 (2018-12) documents, around 50-60Mbps bandwidth is required over the mobile network for V2x services, which support higher autonomy and automation levels. A few foreseeable use cases would require ultra-high bandwidth requirements, like 700Mbps or even 1Gpbs capacity, like 'Video data sharing for automated Driving' or 'Sharing raw data collected by a vehicle's sensors for remote processing.' [4]

At first glance, we might think that 50-60Mbps average bandwidth on Mobile networks is not an issue in 2024. While the average download speed in the top 10 countries is above 110Mbps, only 54 of the measured 111 countries provide more than 50Mbps bandwidth on average, and only 41 of the 111 countries provide more than 60Mbps.

#		Country	Mbps
1	+1	United Arab Emirates	359.85
2	-1	Qatar	343.84
3	-	Kuwait	232.12
4	+2	South Korea	139.38
5	-	Denmark	133.65
6	-2	Norway	132.07
7	+2	Netherlands	128.80
8	-	Saudi Arabia	124.97
9	-2	China	122.79
10	-	Bahrain	112.65

Figure 27. TOP 10 Countries on the Median Country Speeds list Updated July 2024. Source: https://www.speedtest.net/global-index

Germany is in the #43 position with a 57.02Mbps median download speed. (For comparison, five years ago, in April 2019, Germany was in the #45 position with 32.56 Mbps on this list)

Unfortunately, such thorough information is only available for the road system. However, some interesting publications were made in 2023: the first by Bundesnetzagentur, the German regulator, and the second by Deutsche Telekom.

(...)
Strengthening rural areas
(...)
Each of the three established mobile network operators would be required to provide the following minimum coverage:

- 50 Mbps for 99.5% of the surface area from 2030;
- 100 Mbps for 99% of households in rural communities in each federal state from 2029;
- 100 Mbps for all federal roads from 2029;
- 50 Mbps for all regional roads and inland waterways from 2029; and
- 50 Mbps for all district roads from 2030.

(...)

Figure 28. Bundesnetzagentur: Con-sul-ta-tion on ex-tend-ing mo-bile spectrum usage rights, May 2024.[35]
https://www.bundesnetzagentur.de/SharedDocs/Pressemitteilungen/EN/2024/20240513_PKE.html

The German regulator requests a minimum 50 Mbps throughput over the 230.000 km regional road system by 2030 and a minimum of 100 Mbps for around 50.000km of road. It also requests a 99.5% geographical coverage with a 50Mbps minimum throughput, which would improve the vast majority of the 400.000 km local road system.

In May 2023, Autobahn GmbH and Deutsche Telekom announced a cooperation to increase the mobile speed to 200Mbps by 2027 for Germany's 13.000 km-long Autobahn network. [36]

So, there is some good and bad news regarding mobile network throughput. Good news like:

- Regulators pay attention to geographical coverage and throughput, including roads.
- Service providers are increasing the mobile network speed on some sections of the road system.
- Technology is available to support very high bandwidth by the carrier-aggregation feature, which is already available in most mobile networks. This feature enables parallel communication over multiple frequency bands and could result in a Gbps throughput for a user device if multiple frequency bands cover the location.

Unfortunately, there is some bad news from ensuring the required throughput. One issue is that the V2x services require *50-60Mbps upload* (UL) speed and not download (DL). The reason is simple, e.g. steering the vehicle remotely and sending down (DL) the new speed and direction coordinates or values to the vehicle could be done via short messages. *However,* transmitting all information collected or produced by the vehicle would require high UL bandwidth.

If you consider the UL *speed* values from the same speedtest.net source, we might understand the challenge: the global upload speed is only 11.22Mbps.

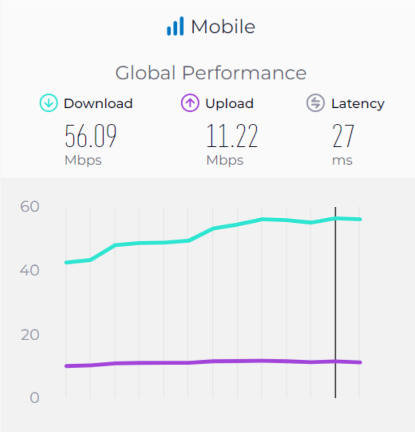


Figure 29. Speedtest Global Index: Global Performance in July 2024. The x-axis represents the last 12 months.
Source: https://www.speedtest.net/global-index

The situation is similar in Germany.

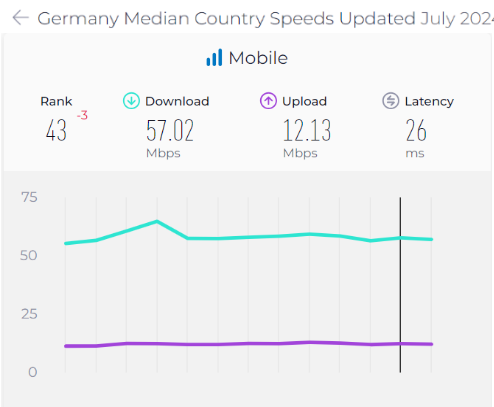


Figure 30. Germany Median Country Speeds Updated July 2024. The x-axis represents the last 12 months.
Source https://www.speedtest.net/global-index/germany#mobile

Ookla measured a 12.13Mbps median upload speed in Germany. *(For comparison, five years ago, in April 2019, Germany had 11.63 Mbps.)*

There are two main challenges to significantly increasing the UL speed. The first challenge is that Operators traditionally prioritise Download traffic over Upload traffic. Traffic directions are controlled by a Channel allocation mechanism. Mobile operators set the UL and DL ratio based on the available radio channels. Traditionally, more channels are allocated to downlink than to uplink, as the ratio is typically 3:1 or 4:1. These channel allocations might need to be changed, especially when targeting multiple 100Mbps Upload traffic.

The second challenge to increasing Upload traffic is the terminal capabilities. Current mobile phones or terminals, in general, are designed for receiving high amounts of traffic and are not capable of transmitting multiple hundreds of Mbps to the radio antennas because it would require much more power capacity today. Engine-powered vehicles might not have power restrictions for transmitting data.

In summary, providing the required bandwidth for the entire road system will likely not happen in the following decades because of the tremendous investment required and its questionable profitability. Network capacities will be gradually built, starting from higher utilised roads, like highways, to lower utilised local roads. However, network development shall be flexible enough to prioritise highly utilised local roads over less-utilized state or interstate roads. Vehicles shall select the most critical information to share on roads with lower available Upload speeds, such as the parameters of their move and share information about other passive objects in the traffic. Traffic management application functions might be limited, too.

9.3 Building up the proper network: *Latency*

The speed of the traffic management solution depends on the required time for collecting the information, calculating the next step, and transmitting the orders to the vehicles. The speed of the calculation depends on the application's speed, and the speed of information collection and order transmission depends on the mobile network's latency.

For simplification purposes, the application speed will be ignored from now on in the overall traffic management solution. The reasoning is that ultra-high-speed SW applications with microseconds response time are available even today, e.g., in the Fintech sector. Another reason is that 3GPP latency KPI values have already been defined considering the expected application speed.

Network latency primarily depends on the distance between the User Equipment, in our case, the active and passive objects in a traffic situation, and the target application, which is the central traffic management application. Therefore, the location of the traffic management application in the mobile network is crucial.

3GPP defined the expected latency values, as we already seen above. Which is “Latency down to 3ms among UEs and 5ms between UE and V2x applications". These values are considered one-way latency, “ *...from the moment it is transmitted by the source to the moment it is received at the destination…*" [4]. Network performance information typically uses Round Trip Time (RTT) values for latency, which covers the time from the source to the destination and back to the source.

Unfortunately, service providers or network performance measurement companies do not publish detailed latency information for different area types. Published information is available with country granularity.

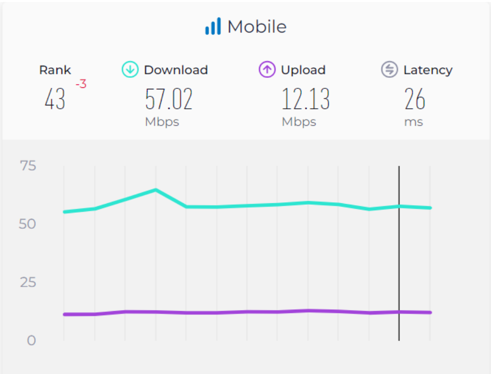


Figure 31. Germany Median Country Speeds Updated July 2024. The x-axis represents the last 12 months.
Source https://www.speedtest.net/global-index/germany#mobile

Figure 31 shows a 26ms latency/RTT value for Germany. Ookla measures the latency between user equipment and the nearest of Ookla’s 15.000 global test servers. The 26ms latency is an aggregated value of all the test samples in Germany in a month. The measured aggregated latency value does not satisfy 3GPP requirements. While the assumption is that the latency is geographically not distributed equally, higher population density areas have better than 26ms latency, and lower density areas have worse latency, there is no available information with the required granularity to understand the size of the potential regions satisfying the 3GPP requirements. Figure 32 depicts a sizeable mobile network topology with the traffic flow between the user equipment and the Ookla server.

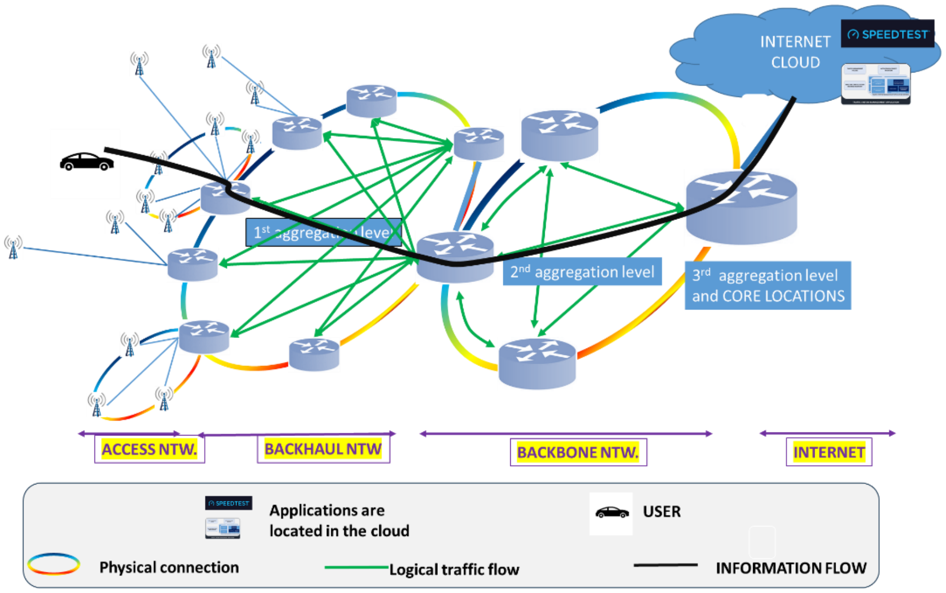


Figure 32. A possible test flow for latency tests is marked in a black line between a car and the test server located on the internet, depicted as “SPEEDTEST”. The network topology is represented by physical and logical traffic paths, highlighting the different network sections of large networks.

According to the Speedtest latency results, the location of the traffic management application needs to be closer to the user than Ookla’s Speedtest servers. Because we don’t know the exact locations of the Ookla test servers, we could try to check another option of using public or private clouds for application hosting. While we don’t have latency information per service providers’ private clouds, the latency information is available for the public clouds. Figures 30 and 31 show the latency between Amazon or Google cloud data centres and a mobile phone on 4G in a high-density area in Germany.

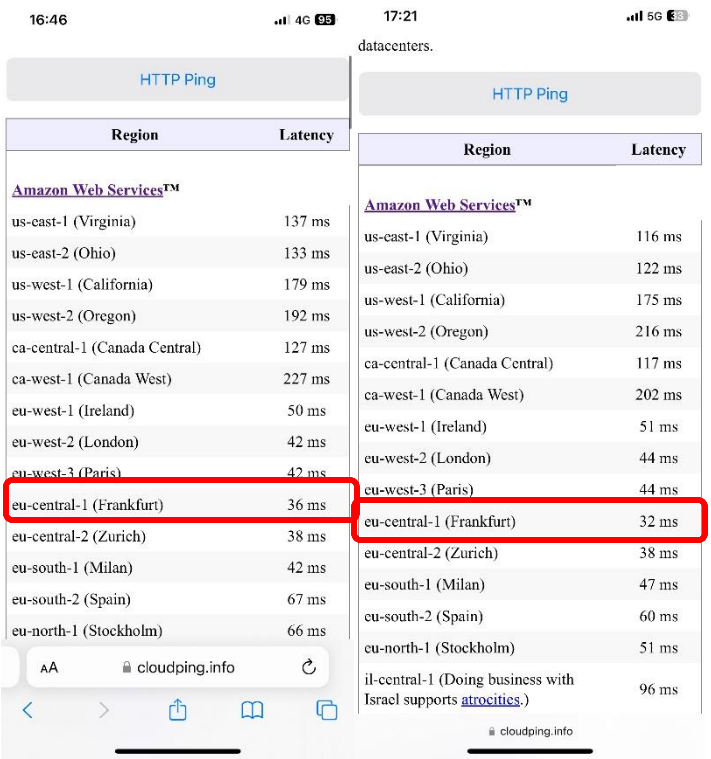


Figure 33. RTT latency between a mobile handset connected to a 4G network (first picture) and a 5G network (second picture) in a dense urban area in Germany and the different AWS data centres in September 2024. The lowest latency is 36 ms between Frankfurt and the mobile handset on 4G and 32 ms on 5G. Source: Michael Leonhard, cloudping.info

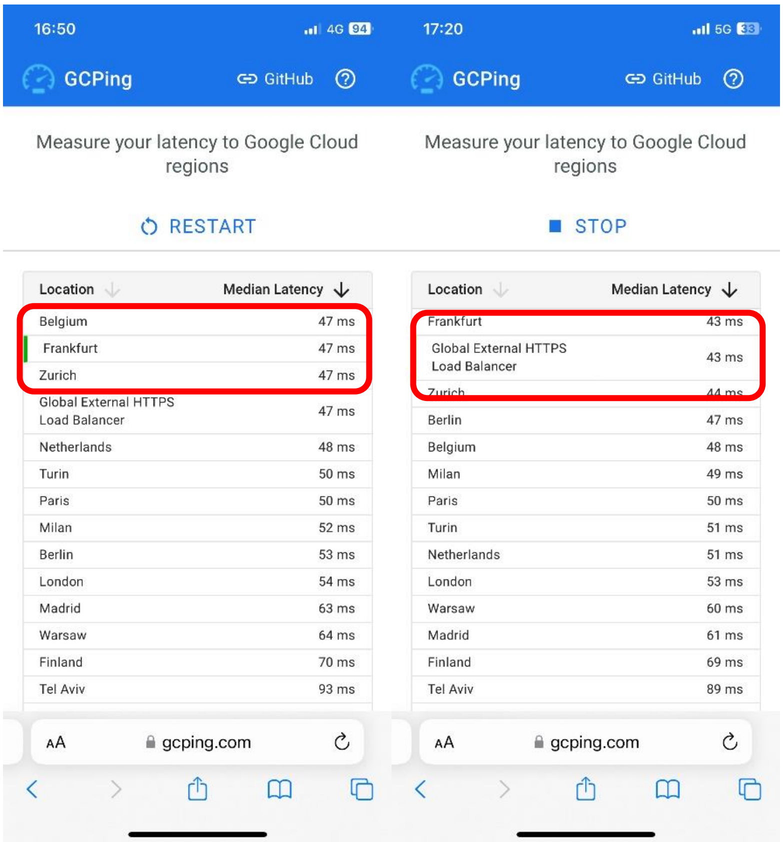


Figure 34. RTT latency between a mobile handset connected to a 4G network (first picture) and a 5G network (second picture in a dense urban area in Germany and the different Google data centres in September 2024. The lowest latency is 47 ms between Belgium, Frankfurt or Zurich, and mobile handsets on 4G and 43 ms on 5G. Source: https://www.gcping.com/

According to these latency values (which are more indicative than representative ones), neither AWS nor Google cloud locations provide the requested latency of 6ms or 10ms RTT on 4G or 5G; however, locating some functions of the traffic management application in public clouds would bring benefits, because of supporting the horizontal and vertical scalability of the application. Latency-sensitive application functions need to be located deep in the service providers' network, and private and public clouds could host applications more relaxed than 50ms-100ms RTT latency requirements.

We have two options for lowering the latency values between UE and the applications:

- Moving the application locations closer to the user.
- Minimising or optimising the shortest path in the network

In the first decades, Mobile networks were typically deployed for coverage requirements, the number of users, and the expected bandwidth per connected device. Increasing throughput was the ultimate driver for a long period, and latency requirements started being considered much later, only in recent years. Service providers are facing a challenge in transforming a brown-field, throughput-optimised network into a network that supports Low latency and high Mobility requirements raised by the Advanced 4G and 5G use cases.

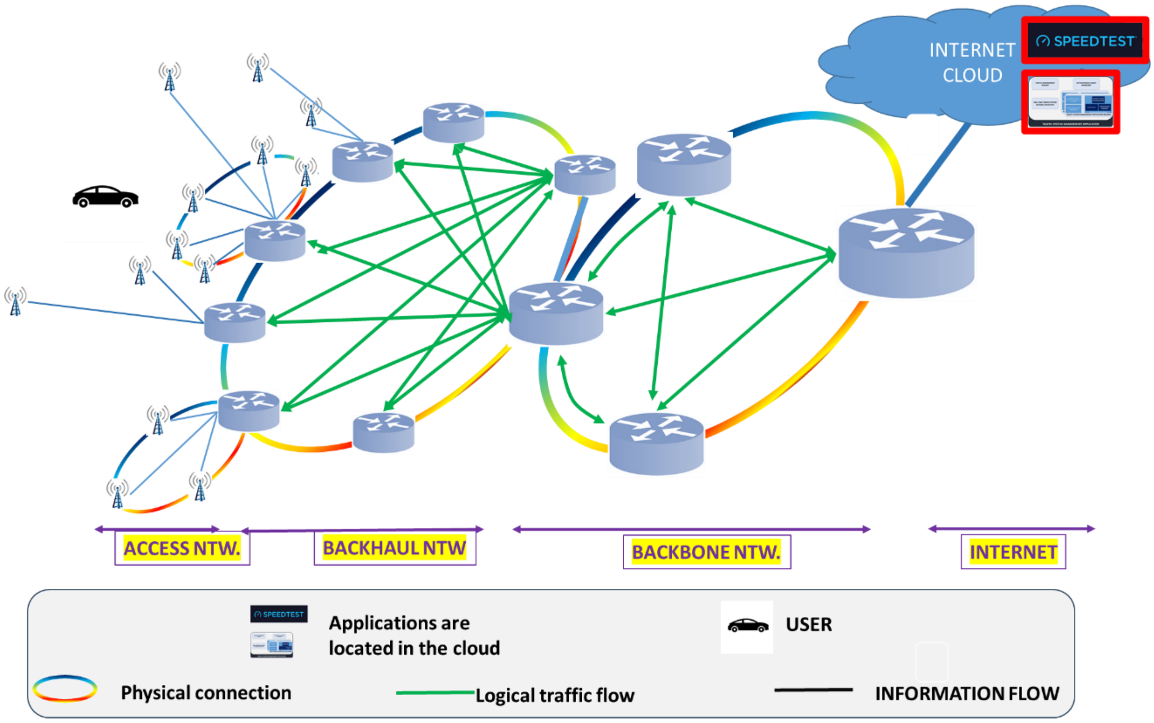


Figure 35. A generic topology of an extensive mobile network from the User Equipment to the internet.

Figure 35 depicts a generic topology of an extensive mobile network. From the access network on the left to the internet on the right. There are three main layers with dedicated physical structures hosting IP routers. The access network connects the mobile base stations or any other customer-premise equipment to the network, typically via optical links or microwaves on the physical layer and a p2p connection on the IP layer. Multiple access networks could be connected to the regional backhaul network, which aggregates access traffic on a regional level and forwards the traffic to the backbone network. One or more physical backhaul networks are split into multiple logical IP areas, sometimes with dedicated optical structures. Typically, a lower-level router is dual-connected to two higher-level routers for the

sake of resiliency. The backhaul network is connected to the backbone network. The backbone network aggregates the traffic from the backhaul network and provides connectivity among the leading data centres. One or two physical backbone networks are present in a larger county. The data centres are connected to the internet.
Ring topologies are often used in the physical and optical layers, as they provide a cheaper option for connecting multiple sites from a lower network layer to a higher network layer. There are other topology options, like star topology with point-to-point connections between the different network layers; that solution is more expensive as it requires more physical links.

Typically, a network layer is built with common physical ring topology and point-to-point logical IP connections. As load balancing is often used on the IP layer, ring topologies in the optical layer typically do not deliver the shortest point-to-point distances, as a portion of the traffic takes one direction in the optical layer, and the other portion takes the other direction.

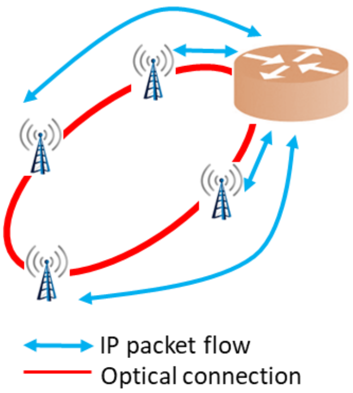
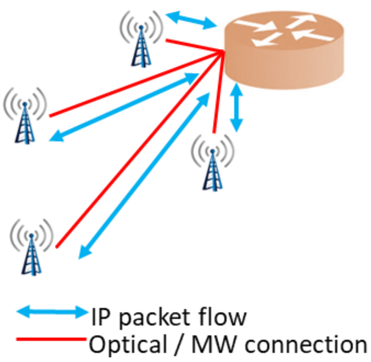


Figure 36: ring optical topology and star IP topology. These connectivity options are typically used in the' old' networks' lower and higher aggregation layers.

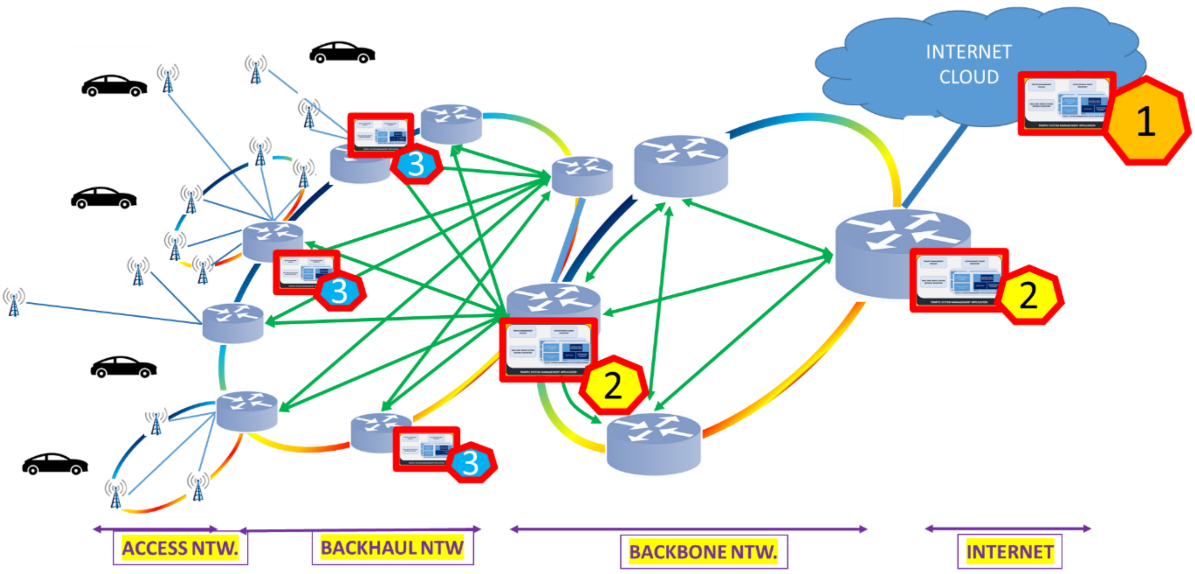
A star topology in the optical layer could typically provide shorter physical distances between the mobile site and the application location. By the way, microwave links in access networks are often deployed in start topologies.



Picture 37: Star topology for both physical and IP layers. The picture depicts the connectivity between the mobile site and the first aggregation layer.

9.3.1 Moving the application locations closer to the user.

Moving the application locations closer to the user is an option for delivering lower latency between the application and the user equipment. Different locations might be available in the transport network for application hosting. Most likely, these locations are the connection points where a lower aggregation network is connected to a higher aggregation network, as from these points, the whole lower aggregation network could be served by the application with similar KPI values. The application locations shall offer infrastructure, like space and power, for the application-hosting environment. This location concept is similar to the Mobile Edge Computing (MEC*)* location concepts.



Picture 38: Possible application locations marked with numbers 1 to 3 in a service provider networks

marks the option when the traffic control application is located in the cloud at a cloud provider location. In this case, the same application is accessible from the entire network. This location could support most of the KPI values requested by the traffic management application; however, latency and mobility remain challenging.

Option 2 provides a location in the service provider's backbone network 

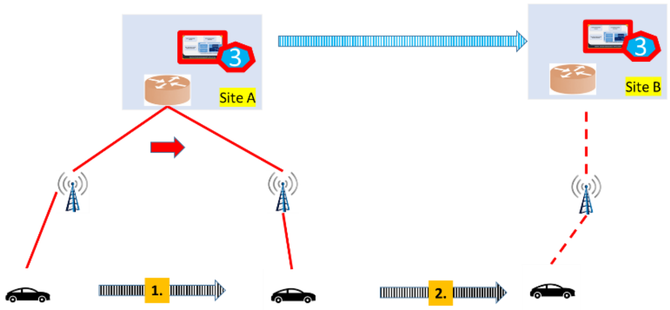
, typically in the data centres. This location could also support most of the KPI values; however, it provides a better latency for two reasons. One is the latency and mobility gain between the cloud and the backbone network, and the second is that the data centres are geographically distributed in the backbone, which provides a further latency gain between an application located in the distributed data centre and the customer equipment in the access network. This option has the challenge of providing the infrastructure for application hosting in the service provider's network, like space and power, versus the practically unlimited resources of the cloud solution,

Option 3 provides a location even deeper in the service provider's backhaul network and closer to the customer's equipment 

. This option supports lower latency, higher mobility KPIs, and capacity management, as the traffic remains relatively local. Application instance accessibility is geographically limited to the connected access networks. Application hosting became a more significant challenge, as the available infrastructure in lower locations is much less compared to the places in the network or to the cloud infrastructure.

9.3.2 Minimising or optimising the shortest path in the network

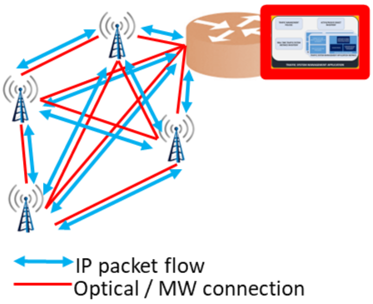
The mobile network needs to provide effective connectivity management among multiple user equipment and between user equipment and applications. This connectivity needs to enable low-latency communication with 3-5ms latency. In parallel, connectivity management must support mobility by providing seamless connectivity over multiple mobile network infrastructure elements, like mobile base stations, while vehicles move.



Picture 39: stateful application connectivity must be provided over multiple physical application location

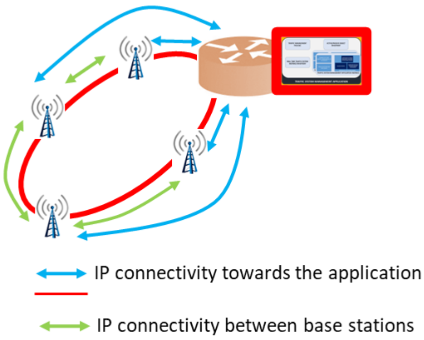
As vehicles move (move marked with 1.) through multiple mobile sites connected to the same mobile connectivity management and application location, the user equipment remains attached to the same application instance in a stateful mode (retains data over time) during the entire move. However, suppose the traffic objects are moving out of the coverage of the actual connectivity management and application hosting area (move marked with 2.). In that case, the traffic management application needs to be prepared at the following application location (Site B) to take over the application in a stateful mode, operate it further and take over the connectivity management of the connected vehicles. While all required technology is available today, there is a massive challenge in the implementation of such a carrier-grade solution with dynamic application orchestration per traffic situation, reserving network resources and providing seamless connectivity for numerous vehicles.

Latency among network nodes is a key capability for effective connectivity management. The most effective connectivity management could be supported by a full-mashed network topology with all neighbour base stations connected to each other and to the application location. In this case, the handover time of a user session among the base stations is the minimum possible, providing the highest possible mobility support for moving objects. Such a topology is very expensive because it requires a high number of physical and logical connections.



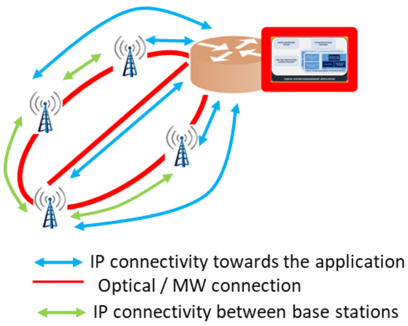
Picture 40: entire mashed topology with point-to-point physical and IP connections among base stations and between base stations and the application.

Unfortunately, many of the topologies in brown-field networks are built up with physical rings. Breaking the existing physical rings and moving to a star topology or implementing a full mashed would be expensive. Optical ring topologies could remain as a trade-off, but new site-to-site logical connections shall be enabled between neighbour sites in parallel to the site-to-application connections. This alternative would decrease the handover time of a user session, thus providing higher mobility support.



Picture 41: physical ring topology with logical connectivity to the application and enabling IP connectivity to neighbour radio sites.

Another possible option in case the latency requirement is too high in some locations is that a relatively low number of point-to-point physical connections could be built.



Picture 42: physical ring topology with a shortcut to support low latency

9.4 In summary.

Service Providers must take the following actions to deploy a mobile network that will support future transportation use cases and the implementation of a central traffic management application.

- Connect mobile base stations to the application location with meshed architecture, ideally directly or via ring topology.
- Replacing actual physical and logical topologies with a more meshed topology to enable low latency and high mobility for applications.

- Enable application hosting at the access, backhaul, and backbone networks, but at least from the backhaul router locations towards the core sites. Roll out the required virtual infrastructure to these locations.
- Enable fast application session handovers among neighbour application locations.
- Implement mobile network resource orchestration to allow dynamic resource allocation per application requirements.
- Enable high upload speed up to 50-60Mpbs everywhere.

10 In the upcoming decades

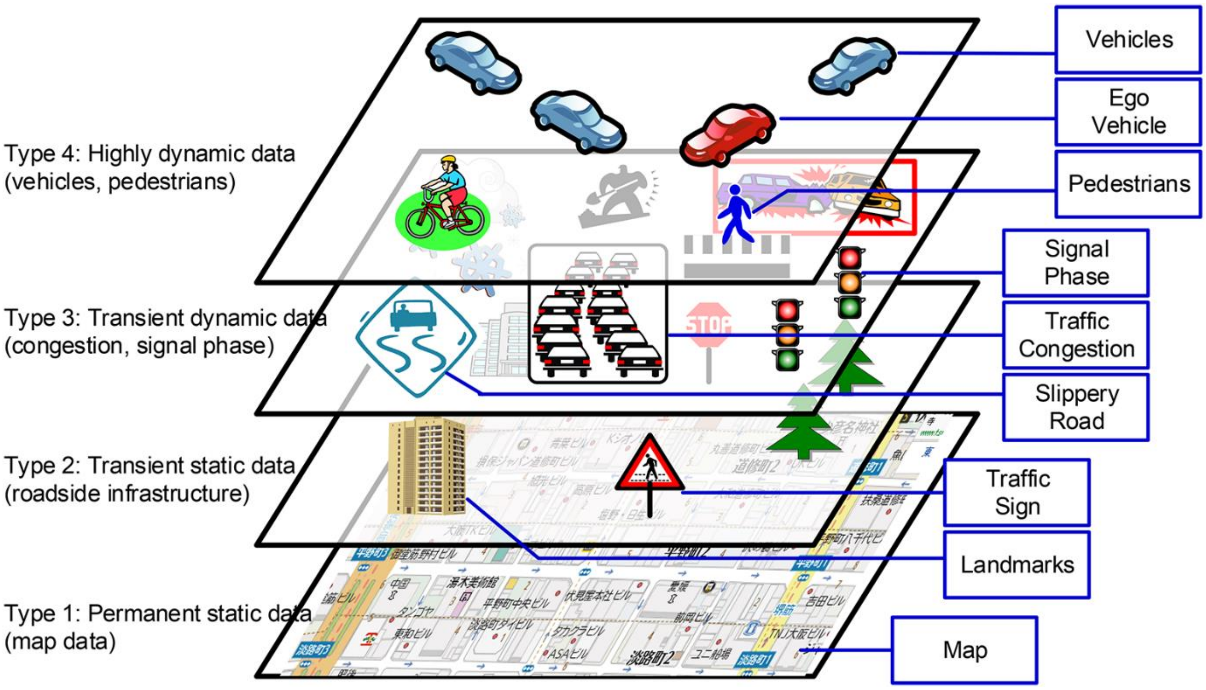
There might be 50 or 100 years until total safety and fully automated transportation will become a reality. The possible achievements for the next ten years:

- Full autonomous driving vehicles will become a reality.
- Automotives keep introducing additional safety features.
- Networks and connectivity options would be further evolved, and future innovations would help to develop cost-efficient solutions.
- Some central traffic management use cases will be implemented, and enhanced traffic management use cases beyond individual autonomous driving will be considered.

11 APPENDIX 1 - Local Dynamic Map (LDM)

Both individual vehicles and traffic support applications need a reliable, dynamic, and real-time view of the traffic. The Local Dynamic Map (LDM) model is developed to provide the required solution.

The concept of LDM is to structure and share all traffic-related information that could be collected with different frequency intervals from stationary objects, vehicles, signals, radars, sensors along the roads, and other traffic management applications. Many route planning, traffic monitoring, and alerting applications already use this model.



Picture 4: the four different layers of LDM [22] based on SAFESPOT Project [23]

LDM concept defines four different layers of information gathering and data processing. Quote from the article **Implementation and Evaluation of Local Dynamic Map in Safety Driving Systems by** Hideki Shimada, Akihiro Yamaguchi, Hiroaki Takada, and Kenya Sato: *'…The first or bottom layer consists of static data, such as road data; the second layer consists of relatively static data, such as signals not included in map data; the third layer consists of relatively dynamic data, such as congestion and other traffic conditions, and the fourth or top layer consists of dynamic data such as automotive sensor information…'*

LDM also described the database structure and interfaces among the different applications and the LDM database.

The LDM concept is over ten years old, and different trial projects have already been completed. For example, the SAFESPOT INTEGRATED PROJECT was completed in Europe in 2010. [23].

The telecommunication industry also uses the LDM model to define the required connectivity among traffic objects. In 2011, ETSI had already considered applications based on LDM, where all relevant data was stored from traffic situations and shared with the vehicle. [19][20]

11.1 Example of potential use cases requesting an LDM solution

In 2016, the European Commission adopted a European Strategy for Cooperative Intelligent Transport Systems (C-ITS). Large-scale deployment of the following use cases was expected by 2019:

11.1.1 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;
- Greenlight optimal speed advisory;
- Probe vehicle data;
- Shockwave damping (falls under the European Telecommunication Standards Institute (ETSI) category ‘local hazard warning’).

The EU expected further services to reach a certain maturity level by 2019, even without rolling out on a large scale:

11.1.2 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.

Regardless of the actual status of these developments, an LDM solution is required to roll out these services.

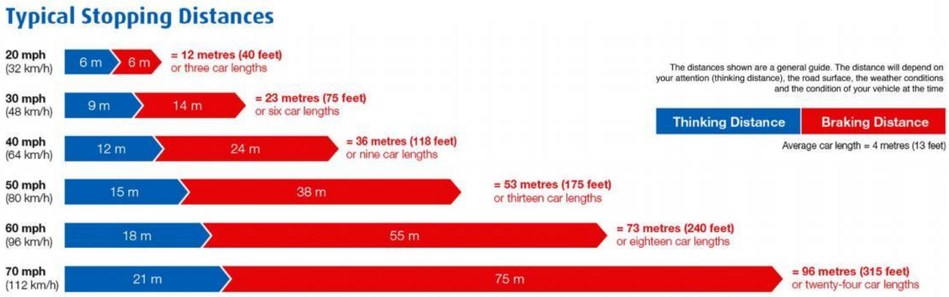
12 APPENDIX 2 - STOPPING DISTANCES

WHY WE NEED AUTONOMOUS VEHICLES AND TRAFFIC CONTROL SOLUTIONS

This chapter defines the speed of the decision-making progress for autonomous vehicles and traffic control applications. The highest level of applied control for a moving object is to stop the move entirely. Therefore, this chapter analyses the options and benefits of reducing the stopping time and distance.

12.1 Stopping distances

The time and distance needed to stop a vehicle summarise two factors. *The total stopping distance is the sum of the 'perception-reaction distance' and the 'braking distance'.*
- *Perception-reaction distance:* the distance taken when perceiving the information and reacting with a move, like pressing the braking pedal.
- *Braking distance* means the needed range to slow down the vehicle to zero.



Picture 11. Total stopping distance is split into Perception-reaction distance and braking distance
Perception-reaction and braking distances. Source: https://www.brake.org.uk/facts-resources/15-facts/1255-speed

The picture above shows the total stopping distances at various speeds. The stopping distance summarises the two phases, represented by the blue (thinking time = perception and reaction time) and red (braking distance) bars. Two comments to the picture:

- In this chart, the perception-reaction time is set to 0.67 seconds, far better than the 1.5, 2, or even 2.5 seconds used by the experts for typical traffic situations.
- Today, the braking distances might be even shorter because the UK Department of Transport published this chart in 2007.

12.2 Perception-reaction time

Perception-reaction time could be calculated in many ways, and different values are used, such as the 0.67% in the previous charts. The relevant quote from Wikipedia:*'...Experts historically used a reaction time of 0.75 seconds but now incorporate perception, resulting in an average perception-reaction time of 1 second for the population as an average; occasionally, a two-second rule to simulate older people or neophyte or even a 2.5-second reaction time—to specifically accommodate very elderly, debilitated, intoxicated, or distracted drivers...'* [6. Braking distance - Wikipedia. https://en.wikipedia.org/wiki/Braking_distance].

Another approach to defining the human perception-reaction time is to use the r*eaction time needed by the human driver to take back control of the vehicle* when the fully automated driving mode is interrupted for any reason. This interruption, disengagement, means *'...When automated driving fails, or is limited, the autonomous mode disengages and the drivers are expected to resume manual driving...'* [25] California Department of Motor Vehicles (DMV) shared the annual report in 2016 with the following companies reported on autonomous vehicle trials from September 2014 to November 2015 in California (Bosch, Delphi, Google, Mercedes-Benz, Nissan, Volkswagen Group, Tesla).

The stable distribution of the time needed to take back the control by the human driver was *0.83 seconds* on average during the trial. [25]

From now on, I use 1 second *as a human perception-reaction time for further calculations below.*

The distance passed in the perception-reaction phase.

distance in meters passed during the perception + recation time	km/h	10	20	30	40	50	60	80	100	130	150	180	210
	m/s	2.78	5.56	8.33	11.11	13.89	16.67	22.22	27.78	36.11	41.67	50.00	58.33
1 second		**2.78**	**5.56**	**8.33**	**11.11**	**13.89**	**16.67**	**22.22**	**27.78**	**36.11**	**41.67**	**50.00**	**58.33**
100 ms		**0.28**	**0.56**	**0.83**	**1.11**	**1.39**	**1.67**	**2.22**	**2.78**	**3.61**	**4.17**	**5.00**	**5.83**
10 ms		**0.03**	**0.06**	**0.08**	**0.11**	**0.14**	**0.17**	**0.22**	**0.28**	**0.36**	**0.42**	**0.50**	**0.58**

Picture 12. Perception + reaction time and distances in meters at various speed

Picture 12 shows the passed distance in meters at various speeds and perception-reaction times. Perception-reaction time is independent of the type of vehicle.

- ***1 second:*** During a 1-second perception-reaction time, the vehicle passes 2.78 meters at a 10km/h speed. At 50km/h speed, the vehicle takes 13.89 meters during the 1-sec perception-reaction phase, and at 210km/h, the vehicle passes 58.33 meters.

- ***100 ms:*** this value might represent a possible perception-reaction time of a machine driver. Machine drivers are supposed to be much faster than human drivers; e.g. Infineon Technologies AG [26] set a 100 ms expected reaction time for a machine driver.

  Such a machine driver could be local, in the vehicle, like the fully automated car itself. Or the machine driver could be remote, in an application in the cloud. In remote driving, *the 100ms perception-reaction time needs to cover the latency time between the vehicle and the application plus the application processing time.*

  100ms of perception-reaction time provides ten times shorter perception-reaction distances than one second. This statement is obvious, and the impact is impressive: at 50km/h speed, the range for the perception-reaction phase is 1.39 meters versus the 13.89 meters required with one one-second perception-reaction time.

- ***10 ms***: This value appears in various standards, like 3GPP TR 22.886 [4], as an overall latency time supported by the network in specific use cases.

  10ms perception-reaction time provides a hundred times shorter distances than 1 second. At 50km/h speed, the distance for the perception-reaction phase is 14 centimetres versus the 13.89 meters required with one 1-second perception-reaction time.

12.3 Braking distance

Braking efficiency is not linear to speed, which means that at lower speeds, the same braking system is more efficient than at higher speeds. However, I assumed that braking efficiency is linear to speed for simplicity and explanation. Without this assumption, considering the total stopping time, the perception and reaction time weight is even more significant than the braking time.

Meanwhile, the perception-reaction time is independent of the vehicle's type; the breaking distance differs between vehicles.

braking distances in meters in dry wether condition	km/h	10	20	30	40	50	60	80	100	130	150	180	210
	m/s	2.78	5.56	8.33	11.11	13.89	16.67	22.22	27.78	36.11	41.67	50.00	58.33
CARS		0.5	2.0	4.5	9	14	20	36	56	84.5	112.5	162	220.5
TRUCKS			3	7.2	12	17.1	27	47.7	68.7	121.8			
TRAM		2	7.8	17.7	31	49	70	125	196	332			
BICYLE		1.57	6.3	14.17	25.2	39.37							

Picture 13. Braking time of the different types of vehicles at various speeds in meters

Picture 13 shows the braking time of different vehicles in typical traffic situations. These could be cars, trucks, trams, and bicycles. [Sources: 7,8,9,10,11]

Cars have the shortest braking distances. Trucks have 30-50% longer braking distances than cars. The trams' braking distances are about 3.5 times longer than the cars' braking distances. The bicycle braking distances are around three times longer than those of cars.

The braking distances might have improved since the related reports were published and used for the calculation. If the braking distances are shortened, the perception-reaction phase plays a more prominent role in lowering the total stopping distances.

12.4 Stopping distances

12.4.1 Cars

The following table shows the total stopping distances for cars.

total stopping distance with various perception + reaction time at various speed	km/h	10	20	30	40	50	60	80	100	130	150	180	210
	m/s	2.78	5.56	8.33	11.11	13.89	16.67	22.22	27.78	36.11	41.67	50.00	58.33
CAR - 1 sec		3.3	7.6	12.8	20.1	27.9	37	58	84	121	154	212	279
CAR - 100 ms		0.8	2.6	5.3	10.1	15.4	22	38	59	88	117	167	226
CAR - 10 ms		0.5	2.1	4.6	9.1	14.1	20	36	56	85	113	163	221

Picture 14. Total stopping distances in meters for cars in good weather conditions at various speeds and various perception-reaction times [Sources: 7,8]

Decreasing the perception-reaction time has a profound positive impact on the total stopping distance at low speed. With 100ms perception-reaction time at 10km/h speed, you could gain 76% of the total stopping distance (0.8m) compared to 1 sec perception-reaction time (3.3m).
At 50 km/h, the car could stop at 15 meters instead of 27.9 meters, which means the total stopping distance is around 13 meters shorter. At 130km/h, the car could stop 50 meters sooner with 100ms perception-reaction time.

Further improvement of the perception-reaction time from 100ms to 10ms doesn't shorten the stopping distance significantly.

12.4.2 Trucks

total stopping distance with various perception + reaction time at various speed	km/h	10	20	30	40	50	60	80	100	130	150	180	210
	m/s	2.78	5.56	8.33	11.11	13.89	16.67	22.22	27.78	36.11	41.67	50.00	58.33
TRUCKS - 1 sec			8.6	15.5	23.1	31.0	44	70	96	158			
TRUCKS - 100 ms			3.6	8.0	13.1	18.5	29	50	71	125			
TRUCKS - 10 ms			3.1	7.3	12.1	17.2	27	48	69	122			

Picture 15. Total stopping distances in meters for trucks in good weather conditions at various speeds and various perception-reaction times [9]

In general, lower perception-reaction time has a similar impact on the stopping distance for trucks as for cars.

12.4.3 Trams

total stopping distance with various perception + reaction time at various speed	km/h	10	20	30	40	50	60	80	100	130	150	180	210
	m/s	2.78	5.56	8.33	11.11	13.89	16.67	22.22	27.78	36.11	41.67	50.00	58.33
TRAM - 1 sec		4.8	13.4	26.0	42.1	62.9	87	147	224	368			
TRAM - 100 ms		2.3	8.4	18.5	32.1	50.4	72	127	199	336			
TRAM - 10 ms		2.0	7.9	17.8	31.1	49.1	70	125	196	332			

Picture 16. Total stopping distances in meters for a tram in good weather conditions at various speeds and various perception-reaction times [10]

Trams' stopping distances are much higher overall than cars and trucks. Like cars and trucks, decreasing the perception-reaction time to 100ms positively impacts trams. *However, because of the approx. 3.5 times higher braking distances, the gain of the 100ms perception-reaction time has a lower impact on the total stopping time*. With 100ms perception-reaction time at 10km/h speed, you could gain 52% of the total stopping distance (2.3m) compared to 1 sec perception-reaction time (4.8m).
At 50 km/h, the tram could stop at 50,4 meters (by 100ms) instead of 62.9 meters (by 1s), which means the total stopping distance is around 13 meters shorter.

A traffic control application needs to manage the trams and trains with consideration of their longer stopping distances.

12.4.4 Bicycle

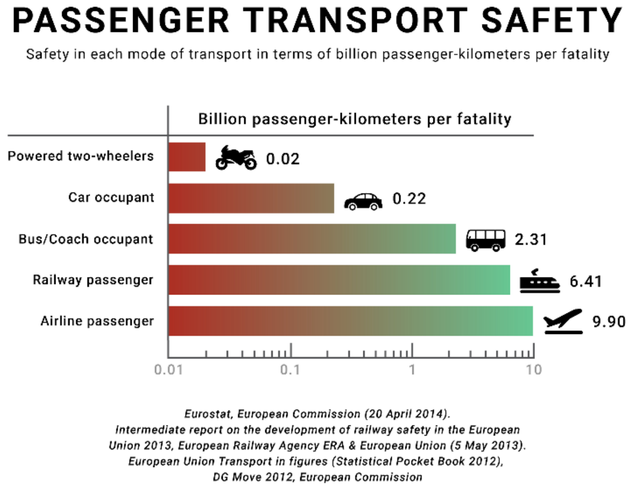
total stopping distance with various perception + reaction time at various speed	km/h	10	20	30	40	50	60	80	100	130	150	180	210
	m/s	2.78	5.56	8.33	11.11	13.89	16.67	22.22	27.78	36.11	41.67	50.00	58.33
BICYCLE - 1 sec		4.3	11.9	22.5	36.3	53.3							
BICYCLE - 100 ms		1.8											
BICYCLE - 10 ms		1.6											

Picture 17. Total stopping distances in meters for a bicycle in good weather conditions and at various speeds [11]

Analysis for bicycles: Bicycle stopping distances are much longer overall than cars and trucks and around 20% better than trams. However, a bike is a man-powered object, so the calculation would make sense with only 1s perception-reaction times.

13 APPENDIX 3 - Safety levels of different transportation methods.

Think about the aviation industry — much higher speed than on the roads and fewer traffic incidents. Even though the aviation industry does not deliver zero casualties, it is much safer than road traffic. It is not easy to find an apple-to-apple comparison between air and road safety, but the ratio could be 1:45 based on compared passenger kilometres. [5].



Picture 10. Fatalities by different transport modes
Source: https://en.wikipedia.org/wiki/Road_traffic_safety#/media/File:Road-ay_vs._railway_safety.png

Picture 10 shows a fatality risk for air passengers 45 times lower than car usage. Based on data from EU-27 member nations, 2008–2010, (Source: https://en.wikipedia.org/wiki/Road_traffic_safety)

There might be two main reasons for the highest safety level in the Aviation Industry. One reason is that the air is less crowded than the roads. The number of objects per traffic system is much lower in the air than on the streets, and the number of different traffic systems is more moderate.

The second reason is that the level of control in the air traffic systems is very high. Detailed regulations and procedures are everywhere. Applied controls are strict, like safety parameters set against the aircraft and rigid and explicit processes during all phases of a flight. Becoming a pilot is more complicated than having a standard driving license. Even getting a pilot license provides much higher control over the quality of the drivers in the air.

You can't put higher entry criteria against getting a driver's license on the roads, nor could you lower the road density with fewer vehicles. However, increasing the level of control is still possible by moving towards automated driving and implementing traffic control solutions.

14 Some thoughts on the responsibility

Who is responsible for a traffic incident and potential casualties after implementing such a traffic control solution? The split of responsibility is similar to the one today in many areas. In practice, there might be three main responsibility areas.

The first set of responsibilities is with the EU or other regulatory bodies, which develop or define the standards for a specific country and issue certificate approvals for industry solutions that meet those standards. The regular body is responsible for developing the proper regulatory framework and defining the standards, specifications and parameters a traffic control solution must meet. The regulatory body is responsible for creating a type acceptance definition with related KPIs for the different elements of the traffic systems and solution, including the vehicles, applications, etc. Also responsible for implementing the proper level of control to validate the compliance of all solutions participating in the traffic themselves and not only relying on the feedback of the solution providers. Similarly, it should be done today. For example, if an accident happens where the drivers were completely following the rules and the vehicle was utterly operating based on the standards set by the regulator, the problem is with the standards and the regulatory framework itself, so theoretically, the responsibility is with the regulator.

The second part of the overall responsibility lies with the solution provider, who must provide solutions that meet the regulation standards throughout the product's lifecycle. Enterprises need to develop products that meet specifications and ensure that quality and capability meet those standards throughout their products' lifecycle. Maintaining their product capabilities could require only reasonable cost and effort from the product owner. If an incident happens because the vehicle stopped operating according to the standards, because a part was broken or dysfunctional, and the owner made all reasonable efforts to maintain the vehicle's capabilities, then the manufacturer is responsible.

The third part of the responsibility is with the user, in general, to use the products and respect the existing traffic rules. In an accident where the regulatory standards were set, and the car operated adequately based on the regulatory standards, the responsibility is with the driver. In practice, you need to develop very sophisticated regulations because even today, sometimes, you can't assign responsibility to one or the other party in an accident.

You need sophisticated regulations to identify which party is responsible for an accident and ensure you cover all the details needed to define such complex systems with the proper regulations.

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