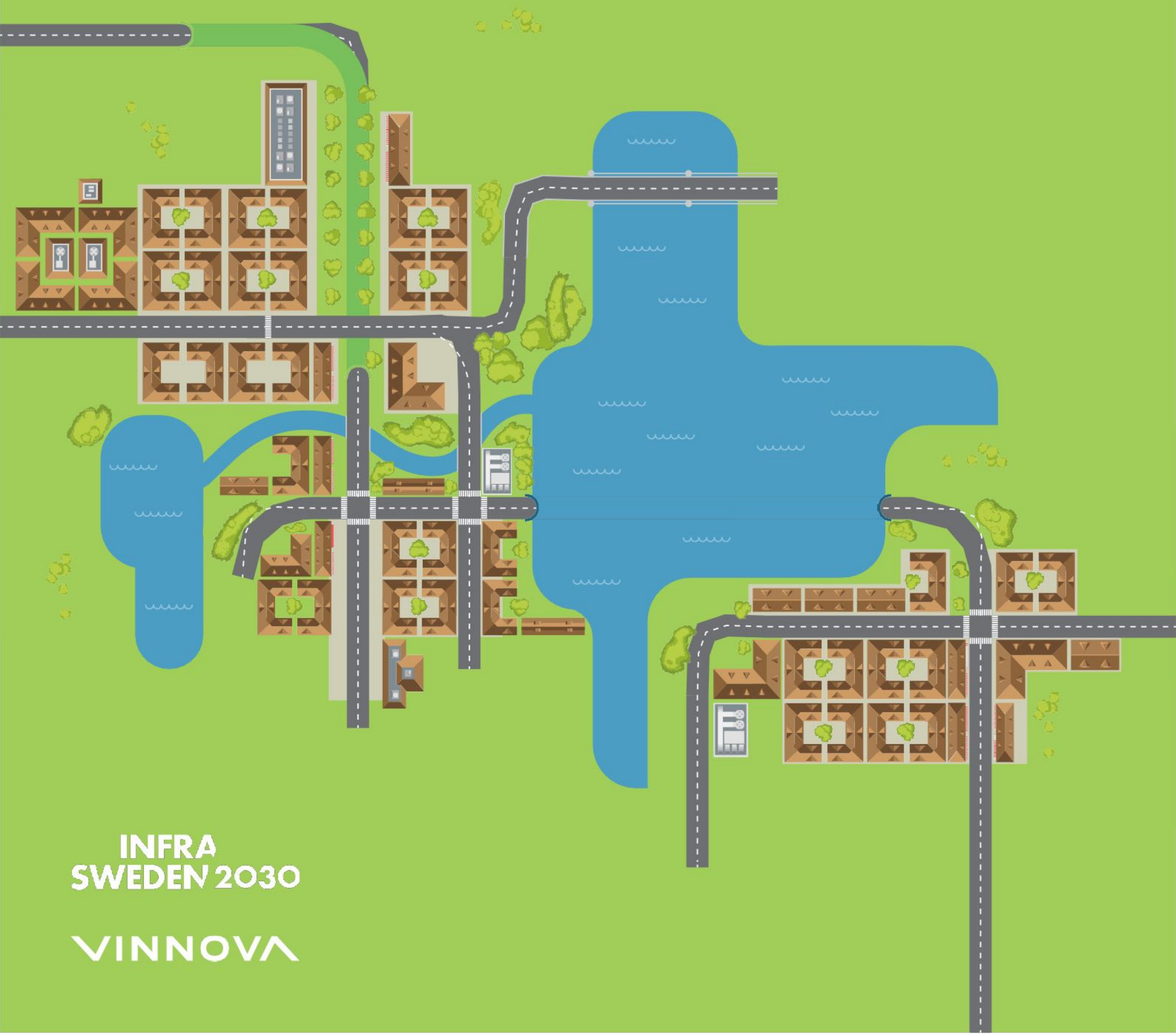
Project: Urban Infrastructure Opportunities with Autonomous Vehicles

Project Number: 2018-00628



INFRA SWEDEN 2030

VINNOVA

NuMo – New Urban Mobility

New urban infrastructure support for autonomous vehicles

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Foreword

All transport systems have a certain capacity determined by its configurations. For cars the most efficient current form is constant speed driving, e.g. the motorway. Its capacity is limited by the time separation between vehicles. Any transport system that stops because of congestion or other causes by definition sees its capacity reduced to zero. Hence traffic jams are hugely disruptive.

Public transport operates on a model inherited from the 19th Century. Vehicles (buses, trams, railways, metros) run on a regular (timetabled) basis and stops at every station (bus stop). Since there is no pre-booking and the need of transport is hard to foresee, the vehicles are often almost empty, at other times hugely congested.

The NuMo technology emerges from decades of work across the whole transportation industry. Autonomous electric vehicles (AEVs) equipped with vehicle-to-vehicle (V2V) communication can safely keep shorter distances. In practical terms this means that a platooned car system has the same capacity in one lane as a double-lane motorway. Automated intelligent controls ensure that the NuMo systems never stops, thus achieving the highest capacity. Instead of waiting for the mass deployment of fully automated vehicles, NuMo starts with dedicated networks that integrate tightly with existing infrastructure for step-wise smooth transition to fully automated transport system.

NuMo includes an on-demand public transport system which only runs when it is needed. The system will take advantage of close-spacing possible with robot controls – vehicles can run close together and also use less road width by less wiggling. Equally importantly stations and access to the normal road network is arranged such that the traffic flow never stops.

The urban impact can be imagined by understanding the impact of modern public transport systems currently under construction. Some of them are underground to avoid disrupting the street patterns. Some are elevated, some rely on physical separation at grade. One interesting option is to use tunnels underground or in water to further reduce disruption. Many cities are abandoning the traditional port infrastructure giving huge opportunities to again regard water as a connector rather than something to cross. The NuMo system uses all of those techniques and detailed design studies are under way for each of those options.

NuMo will make an important contribution to environmental sustainability in many respects. Firstly, it will accelerate adoption of electric propulsion; secondly it will encourage vehicle sharing; and thirdly by only running when needed will save on unnecessary movements and finally its construction costs will be less than conventional systems.

Sketches of NuMo networks are presented on places as diverse as Stockholm, Gothenburg and New York. Naturally the system will also be crucial in the development of new cities.

This report is a summary of the studies performed within the project "New urban infrastructure support for autonomous vehicles" financed by Vinnova through the Strategic Innovation Program InfraSweden2030. The aim is to explore the infrastructure support to accelerate the introduction of autonomous electric vehicles for future mobility.

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Executive Summary

The urban mobility is facing significant challenges with increasing urbanization and mobility demands. The average travel speed in cities is decreasing, mixed traffic leads to inefficient transport system. Traffic safety remains a significant challenge with over 1.6 million fatalities annually from road accidents. The city's most valuable assets – the lands have been taken over by private cars which most of the time are parked.

Challenges come with opportunities. Harnessing the coming transport evolution enabled by the increasing connectivity, automation, and electrification, Autonomous Electric Vehicles (AEV) in combination with business model innovation such as shared mobility has the potential to provide efficient and emission-free transport solutions for future urban mobility. However, AEVs themselves don't necessary lead to efficient transport. Without proper infrastructure support and control, their potential may not be explored, and they may lead to negative impacts on traffic systems and city life. It is thus important to consider the evolution of AEV, the business innovation, together with city infrastructure planning and design to optimize the effects of future automated and electric transportation system.

In this project, NuMo – New Urban Mobility is proposed for step-wisely introducing AEVs into the city infrastructure, starting with existing infrastructure and with consideration on future new infrastructure. In a city without transport infrastructure, NuMo can be applied to plan urban mobility with completely new infrastructure.

The key design principles of NuMo include:

- **Infrastructure segregation:** Separation of AEV from other traffic brings multiple benefits on traffic capacity and safety. The introduction of electric roads and precision control help to reduce the vehicle size and weight, leads to reduced size of road lanes and reduced construction cost for new infrastructure.
- **Higher capacity:** With dedicated infrastructure and vehicle-to-vehicle communication, vehicles can drive in a synchronized fashion, i.e. platooning, and minimize the safe headway to maximize road capacity.
- **Vehicle and infrastructure size reduction:** Thanks to AEV, NuMo design vehicles at 2 x 2.5 x 6 meters (wide, height, length) and this leads to reduced size of road lane width to 2.5 meters instead of current 3.5 meters. A better land and space utilization is thus possible.
- **No stopping on line:** NuMo controls traffic in a non-stop fashion where all stopping should be outside the dedicated network or on off-line stations.
- **Merge-diverge network:** NuMo removes at grade intersections and proposes networks with only merges and diverges to avoid the bottle-necks of traffic.

With the NuMo design principles, infrastructure control principles are proposed that help to enable high capacity urban transport.

- **Intelligent intersection control:** Leveraging the fast introduction of connected vehicle and infrastructure, NuMo proposes local slot booking which allows the intersection to allocate passing sequences to each of the AEVs at the merge intersection.

- **Load balancing:** In NuMo, digital infrastructure allows dynamic routing and navigation for vehicles in the network to minimize congestion. It also allows the redistribution of empty public transport vehicles to serve areas of demand.
- **Safe headways:** NuMo minimizes the headways from 3 seconds from today's manual driving to 1 second, thus maximizing the road capacity.
- **Speed ranges:** NuMo plans for road speed in the 30 – 60km/h range in urban areas and up to 80 km/h outside cities. This considers jointly the capacity, comfort, acceleration and deceleration, as well as the environmental impact.

The NuMo design principles and infrastructure control principles allow high capacity and efficient urban mobility.

- **Capacity:** With speed at 30 km/h, each lane in NuMo can take 3600 vehicles/hour. 4-passenger cars with 1-second headway offer twice the lane capacity of a 24-meter bus with 120 passengers each minute.
- **On-demand mobility:** NuMo is designed to be an on-demand system offering short waiting and non-stop travel.
- **Ride-sharing:** NuMo is designed to be a ride-sharing system with dynamic scheduling. This helps to reduce the negative impact of large numbers of private vehicles.

NuMo is targeting cities with both existing infrastructure and cities that have possibilities to build new infrastructure. A step-wise introduction is introduced to integrate AEVs into the current traffic systems.

- **Sharing the bus lanes and autonomous buses:** Bus lanes provide a semi-protected environment for AEVs, which could be considered as a first integration step with proper plan and coordination. Eventually, buses too will be autonomous and co-exist with AEVs in the same network.
- **New infrastructure:** To complete the existing network to a fully dedicated network, new infrastructure will be built. This could be tunnels, bridges, and even floating tunnels following the design principles of NuMo. The envelope is far smaller than conventional roads and thus far cheaper.
- **One infrastructure, different modes:** On dedicated infrastructure, different modes of traffic can be served. This could be public transport with shared autonomous taxis and minibuses, or private cars and shared cars, or even delivery vans as long as vehicles fulfill the access requirements.
- **Integration with public transport:** NuMo provides design principles for integration with existing mass transit nodes.
- **Electric vehicle charging:** NuMo considers electric roads that allow vehicles to be charged while driving.
- **Infrastructure access control and interaction:** Vehicles must verify the fulfillment of requirements before entering the dedicated network.
- **Emergency procedures:** NuMo has procedures to deal with vehicle breakdowns in the network.

NuMo has impacts on both OEMs and cities.

- **Early deployment and validation for OEMs:** With dedicated infrastructure, NuMo already allows OEMs to test SAE Level 4 autonomous vehicles together with further business innovations.
- **Better utilization of land for cities:** NuMo potentially is able to accommodate future traffic demand with efficient and emission-free solutions, which will allow the cities to return road spaces to e.g., pedestrians and cyclists.
- **Politics are the key:** While developing AEV falls in the hands of OEMs, integrating AEVs into the cities falls in the hands of politics. Integration with public transport, design of new infrastructure, ride-sharing, fares and cross-subsidies will all need strong engagement of politics.

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Introduction

One of the most valuable assets for a city is its streets. Over the last 100 years the city has abandoned this precious resource to an alien invader – the car. We no longer enjoy the essential quality of the street as a social binder, as a pleasant place, as a place to stroll, to walk and enjoy meeting people. While cars have helped our mobility in the past centuries, the current traffic systems fail to provide a sustainable evolution path to address the ever-increasing mobility demand while returning most of the streets to humans.

Significant challenges ahead

Despite the continuous investment on road infrastructure, our present traffic system faces significant challenges.

Speed and capacity

The average speed in large cities is decreasing year by year. In Stockholm inner city the average speed of cars is down to 21 km/h (2015) [1]. Growing traffic volumes in the cause of decreasing driving speeds. During last year (2017-2017) driving speed in major UK cities dropped by up to 20 % according to UK Department for Transport, while traffic rose by only 1.7 %[1].

The most efficient road is the motorway which is segregated from slow traffic and has no intersections. The capacity of a motorway is about 2200 vehicles per hour and lane at this traffic flow the average speed has dropped from 110 to 70 km/h. Other roads have lower capacity [2].

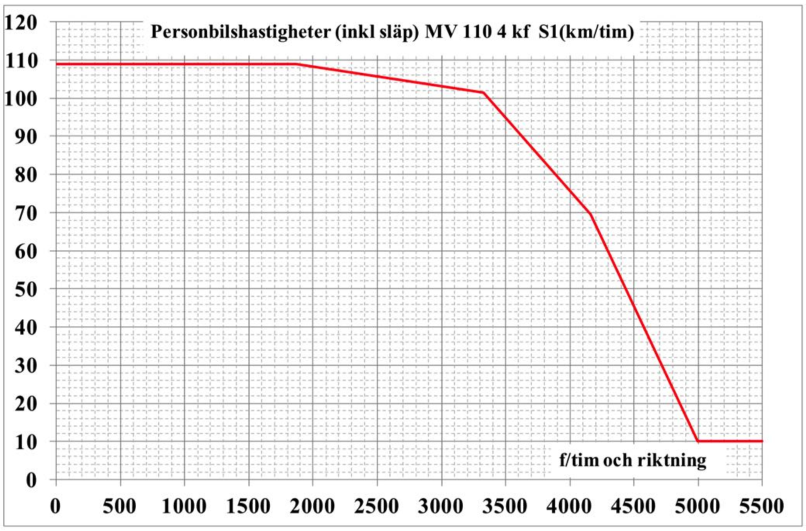

Figure 1 Car speed as a function of traffic flow in two motorway lanes

The reaction time of drivers, (0.5-2 seconds), determines what is a safe driving distance. At 70 km/h the safe headway is about 3.4 seconds while the typical (unsafe) headway in traffic

[1] https://fleetworld.co.uk/average-driving-speeds-plummet-in-uks-major-cities/

is about half of that. A sudden speed change of one vehicle causes shock waves and often collisions between following vehicles.

Trains, buses and trams are large in order to save on driver wages. Their frequency and line capacity are limited by stopping at stations on line. The maximum operating frequency is about one departure per minute. Due to time-table operation the capacity is often poorly used outside the peak hours, as shown by the empty running buses during off-peak hours.

Mixed traffic

Most roads allow all kinds of traffic ranging from cars and trucks to motor bikes and bicycles. Mixed traffic is the cause of many deficiencies in traffic performance. Differing desired speed and different performance cause lane changes, overtaking and disturbances in laminar traffic flow. These disturbances reduce road capacity and cause accidents. Intersections at grade create bottlenecks limiting the capacity of road networks. Signalization reduces accidents but does not solve the bottleneck problem.

Traffic safety

Although Sweden is one of the safest countries in the world, each year about 270 persons (2016) die in road traffic accidents. Worldwide one person is killed each 24 seconds. Causes of accidents include unsafe headways, mixed speeds and human errors (inattention). About 90 % of all accidents involve human errors. Many accidents could be avoided with autonomous driving on dedicated lanes for homogeneous fleets with distance- and speed sensors and vehicle-to-vehicle (V2V) communication.

Land use

Private cars take up a lot of land space. In Sweden some 50 % of city space is dedicated for roads and parking. In California cities up to 70 % of city space is for traffic, parking and related services.

Each car is typically parked 90-95 % of the time – at home, work or shopping. Sweden has in total about two parking spaces for each car. Public vehicles and shared-use vehicles need less parking spaces. Shared autonomous taxis can move to the next passenger and spend very little time parked. Existing parking space can be developed for other uses.

Opportunities

Cities are recovering the asset of street-space, pedestrian streets proliferate along with cycle paths, trees and other much desired amenities.

Today we have a unique opportunity to speed up this process by harnessing the coming transport revolution – the advent of the Autonomous Electric Vehicle (AEV). The current AEV focus is to replace the driver in all situations, including complex interactions with people, other cars, stray dogs and the multitude of urban realities. This will probably mean that streets are not necessarily recaptured for people, in fact with transport being easier it may lead to an increase in traffic.

Beyond cycling there is still a huge need for convenient and safe transport.

The rise of on-demand transport as exemplified by Uber and Lyft and numerous cars sharing initiatives also point to another revolution which will run hand in hand with AEV's – namely that transport should be on-demand and not tied by timetables or fixed routes. This means most transport will also be point-to-point for maximum convenience.

Electrification

With almost all vehicle OEMs announcing plans to go electric, increasing acceptance of consumers, as well as the governments' motivation to go fossil free transport, it is obvious, future vehicles will be electric. In Norway, electric vehicles already make up nearly half the market[2] while global electric vehicle market is projected to reach 567,300 million USD by 2025, with Compound Annual Growth Rate (CAGR) of 22.3% from 2018 to 2025 [3]. At the same time, electric roads where vehicles are able to get charged while driving are also under intensive experimentation and testing. After years of testing at closed spaced in Sweden the first electric road in the world opened near the city of Gävle in 2016, and following that, more electrical roads are opened and planned. With on-road charging, future vehicles will be able to carry much lighter batteries, and do not need to stop for recharging.

Electrification introduces both opportunities and challenges for new infrastructure design. AEVs have zero emission and low noise driving. With smaller batteries, NuMo can design infrastructure to carry much lighter vehicles. This will most probably reduce significantly the cost of building above-ground bridges and under-ground tunnels and affect the construction methods. In the meanwhile, the complexity of integrating, planning and control of the infrastructure increases and require further research together with the electric roads testing. Environmental impacts will be very different in comparison with traditional roads on which further research is needed.

Connectivity

Connected vehicles are on the way with already majority of the vehicles connected through cellular or V2V networks. Cooperative intelligent transport systems (C-ITS)[3] [4], where vehicles are able to communicate with each other and with the road infrastructure are under pilot studies worldwide and are expected to be implemented worldwide. Japan has already commercial C-ITS systems that allow vehicles to communicate with road infrastructure. In the US, the department of transportation (DOT) has been running the connected vehicle pilot program at different cities and has issued a Notice of Proposed Rulemaking (NPRM) that would enable vehicle-to-vehicle (V2V) communication technology on all new light-duty vehicles. In the EU, pan-European pilots of C-ITS cover most European countries such as the on-going C-ROADS[4], and NordicWay 2[5].

Meanwhile, the evolution of dedicated short-range communication (DSRC) and 5G networks enable connectivity with very high reliability and latency which is expected to support many autonomous vehicle applications. The telecom industry has listed automotive as one key vertical industry for 5G, and standardization of 5G networks to fulfill automotive requirements has been on-going. Automotive OEMs also establish alliances such as 5G automotive association 5GAA to focus on communication solutions for future vehicles. In general, it can be concluded that future cars will be connected with capability of super-fast

[2] https://www.weforum.org/agenda/2018/09/electric-vehicles-are-half-the-market-in-norway/
[3] https://ec.europa.eu/transport/themes/its/c-its_en
[4] https://www.c-roads.eu
[5] http://vejdirektoratet.dk/EN/roadsector/Nordicway/Pages/Default.aspx

data connection, and ultra-low latency and high reliability communication for active safety. NuMo is based on the evolution of connectivity and considers such connectivity as an integral part of future cars and infrastructure for vehicle collaborative driving, intersection control and so on.

Automation

There are many transport precedents to the NuMo system. World-wide trials of autonomous vehicles have been in the headlines in recent years, and major car manufactures, and Internet giants all announced their plans for future AVs. Vehicles with automation level at SAE Level 4 [5] already appear on dedicated areas.

There have been widespread trials of autonomous mini-buses, such as the ones in Stockholm[6] and Gothenburg[7]. There are numerous manufacturers of these vehicles, two in France, one in UK, several in the US, China and Japan. The restriction on all of these is that they are designed to travel only at relatively low speeds, typically at 20 km/h and maximum 40 km/h. While such solutions target first- and last-mile mobility, NuMo targets general traffic and aims at introducing AVs at higher speed, order of 80 km/hr.

One of the interesting precedents is the Ultra Global Personal Rapid Transport (PRT)[8] already in operation at Heathrow airport, which has very similar goals as NuMo to provide congestion free, multi-origin, multi-destination mobility services. However, the design principles are very different. Though the system has dedicated tracks as well as charging facilities, the Ultra pod has a maximum speed of 40 km/h. The Ultra Pod uses a railway similar control system while NuMo will be part of the future smart transportation system relying on future autonomous vehicles and connected infrastructures.

Though with low speed, the benefits of Ultra Global PRT come from the dedicated tracks where the Ultra pods don’t mix with other traffic, thus can run in a non-stop fashion. This also motivates the future AV segregated infrastructure design which is the central design principle of NuMo.

Autonomous vehicles per se are not expected to reduce traffic and congestion. On the contrary, the fact that travel times are more comfortable and even can be productive, may lead to longer commutes, more trips made, diversion from public transport and empty vehicle trips. Ride-sharing is the key to reduced traffic. For a high degree of sharing a fleet of public vehicles should take passengers on demand between dedicated stations. The need arises for segregated infrastructure to achieve substantial carrying capacity. Already the motorway system provides segregated tracks for cars and are relatively easily converted in reserved lanes for AEV only use which would enable a sharp increase in capacity. The issue that new infrastructure needs to address is how that type of system can be extended into city centers. Most cities today have a large stretch encompassing suburbs and urban regions and these settings will be increasingly important (currently roughly 50% of the world’s population live in cities, this will almost certainly increase substantially in this century).

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[6] http://bit.ly/stockholm-shuttle-av
[7] http://bit.ly/chalmers-shuttle-av
[8] http://www.ultraglobalprt.com/

Cities have also been starting to plan the future infrastructure with consideration of AVs. In 2017, the Gothenburg city in Sweden announced their plan[9] to examine the interaction between AVs and the sustainable, long-term urban planning, which is considered the first of its kind in the world. Also, in 2018, it was announced[10] that the Fehmarn tunnel between Denmark and Germany will be adapted for future AVs.

NuMo – New Urban Mobility

To deal with the above-mentioned challenges and to leverage the fast development of autonomous electric vehicles, the rapid evolution of connectivity, as well as the emerging business models such as shared mobility and shared economy, we propose new urban mobility concepts to enable future urban mobility infrastructure and solutions.

The NuMo proposal explores the possible steps in such a transformation by exploring all types of segregated system in dense urban areas such as above ground, at grade, underground as well as an exciting variant of floating tunnels. Ultimately, there will be a complete blurring of the border between 'public' and 'private' transport, where the basic public transport systems such as buses, trams and metros will in time be replaced by on-demand point-to-point AEV's.

The NuMo system explores how such a system will look and perform in the following chapters.

- Chapter NuMo Design presents the NuMo design principles with focus on segregated infrastructure design.
- Chapter NuMo Infrastructure Control and Capacity leverages the fast development of autonomous vehicles and communication technologies which enable different traffic control strategies leading to increased road capacities.
- Chapter NuMo Infrastructure Integration discusses potential integration solutions of AVs into today's traffic systems.
- Chapter NuMo Infrastructure Construction discusses different construction alternatives of NuMo infrastructure.
- Chapter NuMo environmental impacts describes the impacts on environment from the perspectives of energy consumption of the cars, wear particles and noise, as well as impacts of different construction methods.
- Chapter Challenges and further research summarizes challenges ahead and propose further research directions for integration of AVs into future traffic systems.

[9] http://bit.ly/gothenburg-av-city
[10] http://bit.ly/femern-tunnelen-av

NuMo Design

NuMo is a mobility system based on dedicated road networks and AEVs. It eliminates blockages such as on-line stopping in the traditional road network and the needs of traffic mode changes to fulfill one trip. Instead, with dedicated networks and AEVs, NuMo allows vehicles to travel directly from origin to destination. The following part analyses the effects of dedicated space for more homogenous fleets of cars and light vans. With AEVs, the space envelope of such lanes is smaller and can be dimensioned for less weight load. Intersections are limited to merges and diverges between unidirectional traffic streams with vehicles of similar size and performance.

Infrastructure segregation

Segregation is the main design principle of NuMo as this plays the key role to achieve high traffic capacity and ensuring safety at higher speeds. Complete separation allows for the early introduction of autonomous vehicles, avoiding the conflicts associated with mixed fleets of manual and autonomous vehicles. In addition, dedicated infrastructure for homogenous fleets brings many advantages such as limited size envelope, precise lane control and weight reducing space requirements and construction cost. Shown in Figure 2, the dedicated space can be a lane on a motorway or other road, a new lane at grade, an elevated structure or a tunnel.

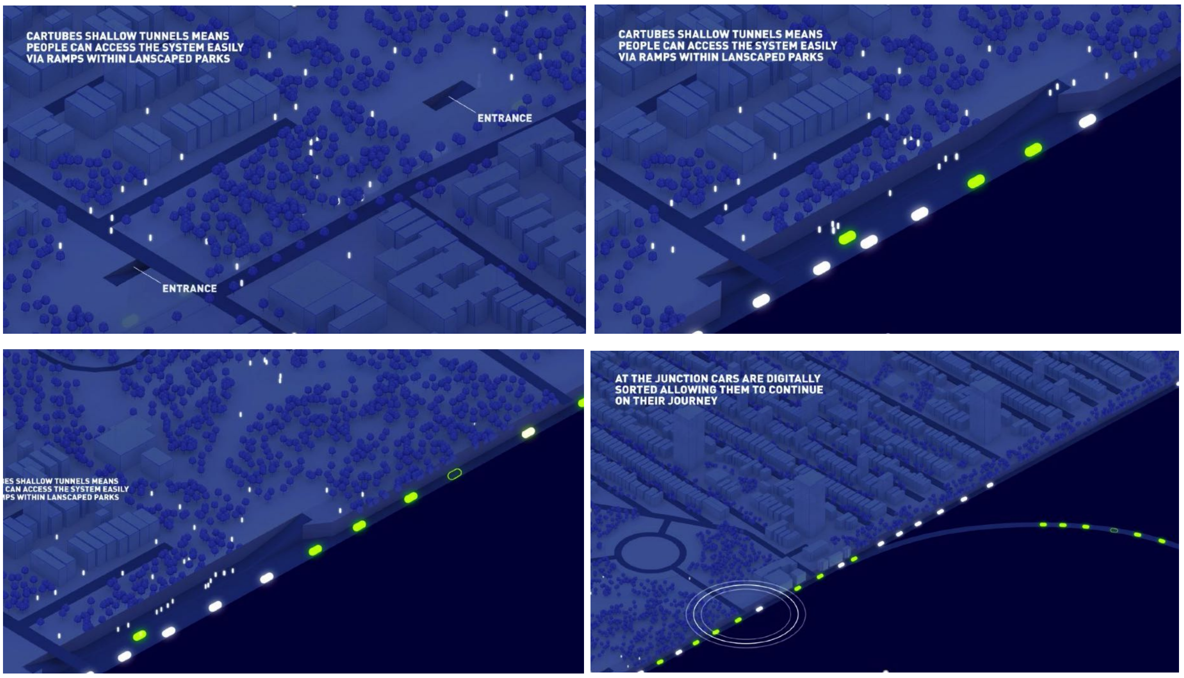


Figure 2 Dedicated guideway for cars and light vehicles

Shorter headways and higher capacity

Allowing only autonomous vehicles on the infrastructure means that they can all maintain the same speed, there is no overtaking and less accidents. Autonomous vehicles with sensors to detect distance and speed have shorter reaction time and therefore allow shorter headways and higher lane capacity. With vehicle-to-vehicle (V2V) communication and synchronized braking even shorter gaps are possible.

Vehicle and infrastructure size

A current motorway lane is usually between 3.5 and 3.7 meter. In the NuMo design the vehicle envelope is set at 2-meter wide, 2.5-meter high and 6-meter long. With the greater accuracy of control, the design assumes a lane width of 2.5 meters. NuMo explores both single lanes and double lanes. The solutions will depend on requirements and also costs associated with each type. Excavated tunnels are significantly more expensive than floating tunnels or elevated systems.

Figure 3 illustrations the reduction in size of tunnels and their impact. It is expected the increase in capacity in the NuMo system essentially reduces the number of lanes compared with a conventional road. The comparison is therefore made between 3 lane conventional road (with a vehicle height clearance of 4.5 meters) and twin lane NuMo, and between 2 lane conventional road and single lane NuMo.

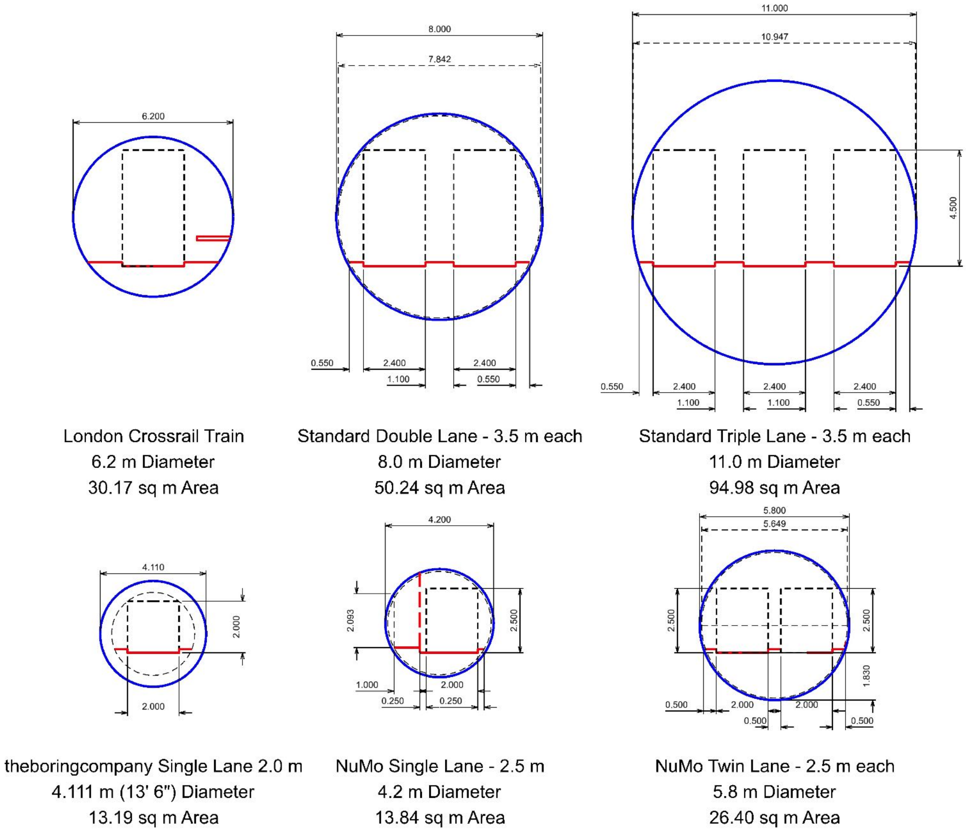


Figure 3 Tunnel size reduction in NuMo will lead to reduced costs and increased capacity

A large proportion of costs in tunneling is in the volume of material excavated, which is directly proportional to the cross-section area of tunnels.

The conventional tunnel in both cases is 3.6 times as large, implying a cost difference of the same order of magnitude. This would mean in effect the NuMo system could cost a third of conventional systems.

Innovation in tunneling technologies have been relatively slow. The new entrant of Elon Musk's the Boringcompany into the field could potentially change this just as the Tesla electric car has changed OEM's approach to electric vehicles. The tunnels proposed by the Boringcompany are similar to those proposed under the NuMo system.

The comparison with London's Crossrail also illuminates the fact that a twin lane NuMo tunnel with potentially similar capacity and far greater flexibility could be the way forward for urban mass transport.

No stopping on line

NuMo proposes non-stop traffic where no stopping is allowed on the dedicated space. All stopping should be outside the network or on off-line stations. Parking will not be allowed in these stations to be used for passengers getting on or off. Parking spaces for private vehicles will be outside the dedicated network.

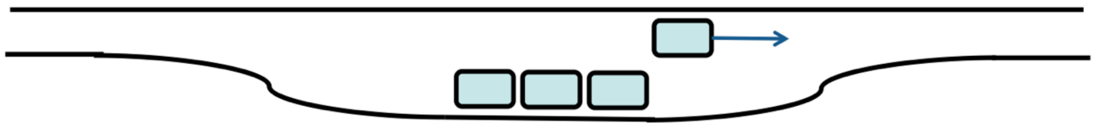


Figure 4 Stopping only in off-line stations

Merge-diverge network

Another design principle of NuMo is to remove grade intersections as they are bottle-necks reducing the capacity of the overall network. NuMo proposes networks that have only merges and diverges like on-ramps and off-ramps on motorways as shown in Figure 5 a one-level network and Figure 6 a two-level network design.

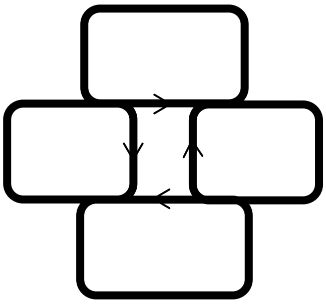


Figure 5 Guideway networks in one level with merges and diverges connecting one-way loops

A network in two levels allows more straight paths in all directions and higher speeds. The network concept in Figure 6 is based on the separation of lanes going in different direction. Unlike traditional roads which have traffic in both directions on the same alignment, the NuMo grid separates the lanes travelling in different directions. By doing that the road junctions are radically simplified. In effect the grid acts as a set of very large interconnected roundabouts. This topology allows off-line stations to be located inside the roundabouts. Conceptually each grid could be of the order of 1 km, meaning that surface distances for pedestrians would never be larger than 500 m. Naturally the topology would be adapted to local circumstances.

The right-angle intersections could theoretically be arranged as at-grade intersections with autonomous controls to avoid collisions. Many experiments to this effect have already been trialed [6]. The NuMo proposed grid circumvents the obvious problems of automated controls by having grade-separated intersections and the control mechanism is limited to merging (and demerging) traffic streams.

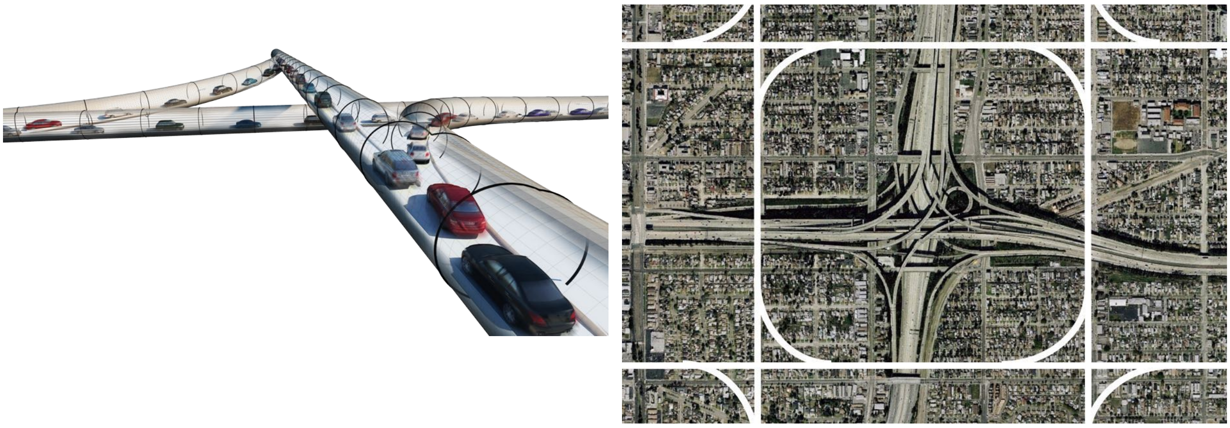


Figure 6 Guideway network in two levels with sloped ramps in intersections, by separating the lanes the intersection geometry is much simplified

NuMo Infrastructure Control and Capacity

The emerging connected vehicles and infrastructure together with big data analysis and artificial intelligence enable new alternatives for traffic control. Traffic control ranges from macro traffic flow control down to individual vehicle control at each intersection. We explore different state-of-the-art principles and propose NuMo traffic control solutions.

Control alternatives

Several control principles are conceivable.

Central control

This is common in so called personal rapid transit (PRT) systems. Each vehicle is controlled from outside with controlled trajectories (path, speed and acceleration). A vehicle can start only when it is assigned booked passage times through all conflict points. This so-called synchronous control has limitations when it comes to large networks and it is not robust against disturbances.

Local wayside control

Local zone controllers control vehicle speeds and accelerations in its zone, typically all vehicles approaching a merge. Central control is only needed for balancing supply and demand with empty vehicles. This so-called asynchronous control can be scaled to large networks and it can accommodate disturbances. Vehicles may have to slow down or exceptionally even queue although the routing is dynamically planned to avoid congestion.

Distributed vehicle-based control

Each vehicle plans its trip and keeps safe distances based on its onboard sensors and V2V communication. This is similar to the way traffic operates today with humans as sensors and actuators. Technology is available for car following but not yet for control in general intersections.

Merge control

In NuMo networks, the only conflict points are the merges where two lanes come together. The above three control principles lead to the following methods for merge control.

Central slot booking

Entry to the system is only permitted after the central booking system has assigned a free path (merge passage time slots) for each trip. All vehicles must keep the common speed for all vehicles. This method is used by Ultra PRT with 21 vehicles operating at Heathrow Terminal 5.

Local slot booking

Roadside units (for example, “traffic signals”) monitor incoming vehicles by V2I communication, assigns and communicates passage slot time. With onboard intelligence each vehicle can plan its trajectory to meet the assigned slot time, such as described as the centralized intersection management in [6].

V2V cooperation

Priority to the first estimated arrival or to the first vehicle on a priority path. The vehicle with priority signals to other vehicles which can then adapt their behavior to avoid conflicts. Vehicles can also negotiate with each other to reach a consensus on how to pass the intersection according to pre-defined criteria.

In NuMo, Local slot booking is suitable considering the fast development of C-ITS, the maturity of standards, and the active engagement of authorities and vehicle industry.

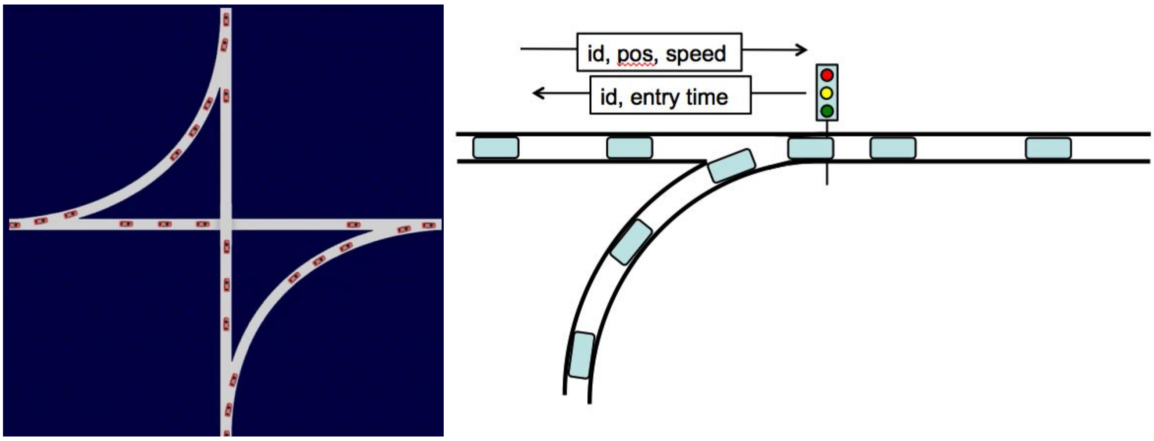


Figure 7 Merge control by allocation of passage time slots

Load balancing in networks

Vehicles with navigators can already navigate to avoid queues and bottle-necks. NuMo will push this further by leveraging the forthcoming C-ITS infrastructure. Digital infrastructure allows road sensors to collect density and speed information and communicate them to vehicle-based navigators for balancing traffic flows to avoid congestion.

Another form of balancing is the redistribution of empty public transport vehicles to serve queueing passengers and expected demand such as arriving trains and special events.

Safe headways

In this section we consider three different safety assumptions and their consequences for distance keeping, safe headways and lane capacity.

The first assumption is manual driving. When a driver takes notice of an action of another car, it takes 1-3 seconds before he reacts, say 1.5 second. During that time his vehicle continues to move at its previous speed. If he decides to brake, it takes about 0.2 seconds to start applying the brakes. The stopping distance depends on the square of the speed and the braking rate – we assume 7 m/sec^2 emergency deceleration. At 50 km/h the safe gap (bumper-to-bumper) with these assumptions is 37 meters.

The second assumption is driverless with sensors and/or V2V communication and safe stopping distances assuming that the previous vehicle may stop instantaneously, a so-called Brick Wall Stop (BWS) as shown in Figure 8. This is a common requirement for Automated People Movers on guideways. The reaction time with sensors and communication is reduced to 0.1 seconds and the safe gap at 50 km/h would be 18 meters.

The third assumption takes advantage of V2V communication so that vehicles can synchronize their maneuvers, so called platoon driving. This is the assumption in NuMo networks.

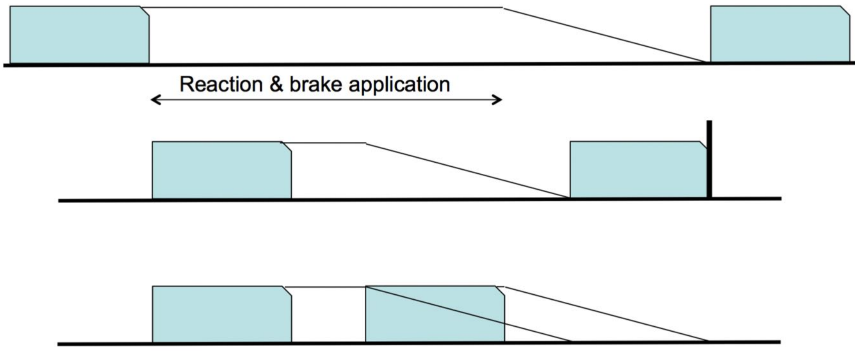


Figure 8 Speed profiles for Manual, Autonomous and Synchronized stop with V2V communication

With the above-mentioned three control strategies, safe gap and headway can be calculated and are shown in Figure 9 and **Error! Reference source not found.**, respectively.

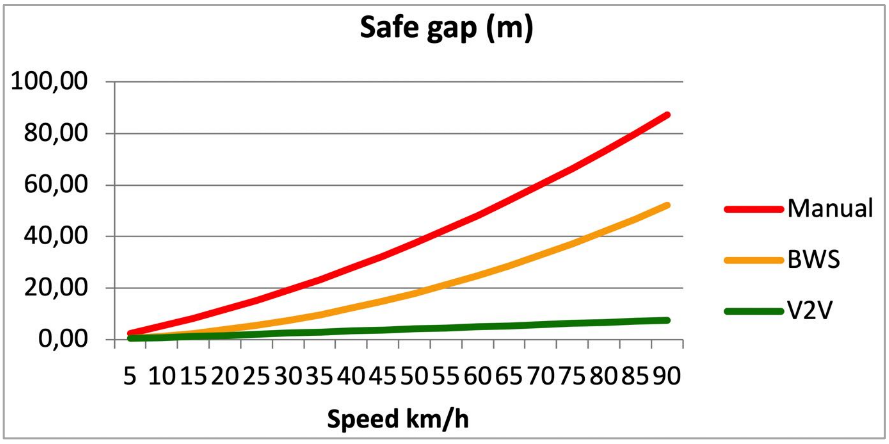


Figure 9 Safe gap between human driver (red), autonomous car at safe stopping distance (amber) and with V2V communication and synchronized maneuvers (green)

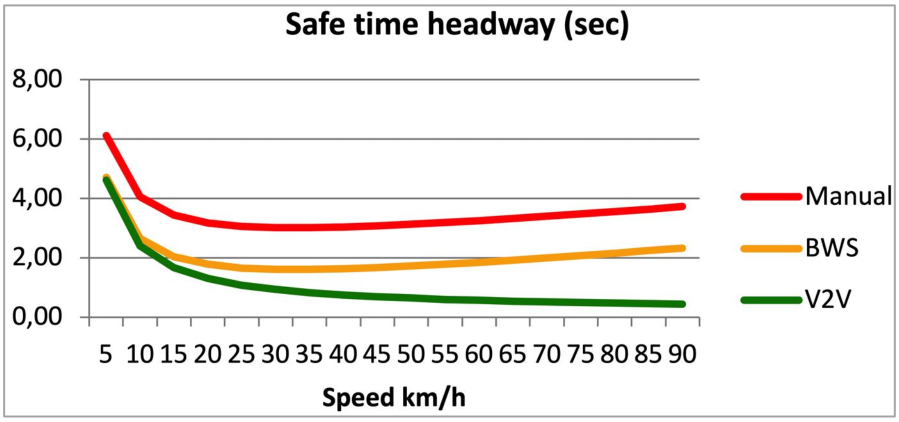


Figure 10 Safe time headways (nose-to-nose) of manual driving, BWS and synchronized maneuvers (V2V)

The time headway (nose-to-nose) determines lane capacity. With shorter time headways, more vehicles can pass in a given time. For a given time-headway, the distance gap increases with speed but not enough to compensate for the increasing stopping distance. Therefore, the safe time headway increases with high speeds except when braking maneuvers are synchronized. At very low speeds the length of each vehicle limits the time headway – otherwise vehicles would overlap.

The minimum safe headway with manual driving is about 3 seconds for vehicles up to 6-meter length. This is the de-facto rule taught in driving school with consideration on human driver reaction time.

With connected and autonomous vehicles, the reaction time is reduced to about 0.1 second and the safe headway allowing for brick wall stops gets reduced to about 1.6 seconds for speeds between 20 and 50 km/h. With consideration of V2V and synchronized maneuvers, vehicles do not need to maintain the stopping distance. Headways of 1 second are possible at speeds over 30 km/h.

In the platooning example, 6-meter gaps (0.5 sec) have been demonstrated in communicating truck platoons at 85 km/h with SARTRE project[11] as shown in Figure 11. That corresponds to 0.5 second headways nose-to-nose for 6 m vehicles. We assume to cap smaller headways at 1 second, although with V2V they could be even smaller at higher speed.

Figure 11 SARTRE project tested platooning on a motorway

Speed range

NuMo speed ranges are decided with consideration on capacity, comfort, acceleration and deceleration at stations, as well as the environmental impact.

We have seen that speeds below 30 km/h would require time headways over 1 second and hence reduce line capacity to below 3600 vehicles per hour.

In the other end of the speed range, vehicle paths need to be straight and smooth for comfort. Side accelerations should be kept below 2.5 m/sec^2 according to the American

[11] https://spectrum.ieee.org/automaton/robotics/industrial-robots/sartre-autonomous-car-platoons

Automated People Movers (APM) standards. That dictates a curve radius ($a=v^2/R$) not smaller than 28 meters at 30 km/h and 77 meters at 50 km/h.

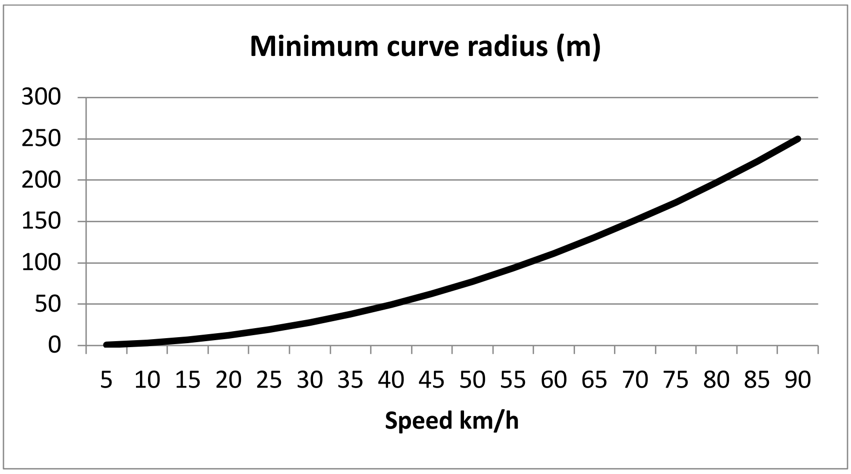


Figure 12 Minimum comfortable curve radius dependence of speed

High speeds also necessitate long station sidings. The stopping and acceleration distances ($s=v^2/2a$) at comfortable braking (2.5 m/sec^2) is 40 meters at 50 km/h. Each off-line station needs to be stopping + acceleration distances plus the spaces needed for stopped vehicles. At 50 km/h an off-line station for three 6-meter vehicles needs to be 95 meters.

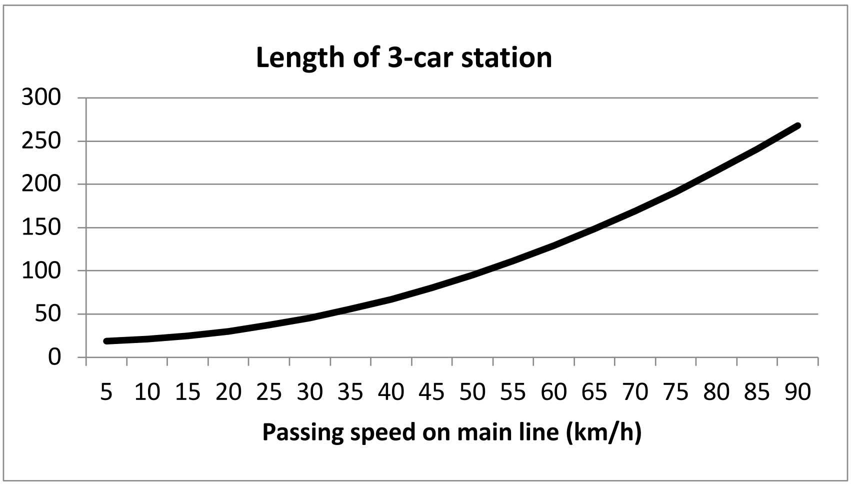


Figure 13 Station length grows with higher passing speeds

In view of the above restrictions and the desire to avoid big speed changes, it may be that systems will be designed for different speeds depending on local circumstances. Speeds could range from 30-60 km/h to 80 km/h. Speeds need to be reduced for comfort in tight curves. Local speed limits (40 km/h) around station bays allow for shorter stations.

Capacity calculations

The time headways determine the lane capacity (=3600/headway). With manual cars each lane can take 1200 vehicles/hour. With sensors and brick wall stopping distances the lane capacity would be 2200 vehicles/hour. With synchronized maneuvers each lane can take 3600 vehicles/hour as long as the speed is at least 30 km/h.

We assume a minimum time headway of 1 second nose-to-nose in the NuMo network. As seen in Figure 10, one second headways are possible at speeds above 30 km/h. As long as the minimum headway remains the same, the capacity is independent of speed. At low speeds the distance gap is smaller. Below 30 km/h one second headways are not possible, or vehicles would overlap. Slower vehicles would result in longer time headways thus reducing throughput and system capacity. Off-line stations and system control ensure speed and traffic flow in the NuMo network.

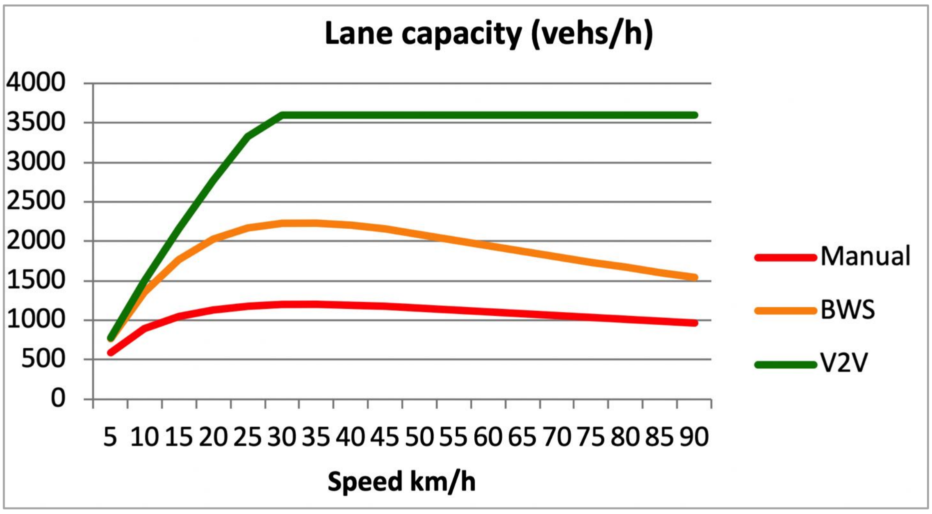


Figure 14 Lane capacity of manual driving, BWS and synchronized maneuvers (V2V)

As shown in Figure 14, based on the NuMo design principles, synchronized maneuvers achieve the highest capacity. The passenger carrying capacity is larger than big buses and trams.

Taking a 24-meter bus and a 4-seat autonomous vehicle as examples and as illustrated in Figure 15, A bus on its own reserved lane can run at 1-minute headway taking 120 passengers. The theoretical maximum capacity is then 7 200 passengers per hour and lane. A 4-seat car with 1-second headway offers twice that capacity. In practice the fill rate will be lower except in peak traffic conditions.

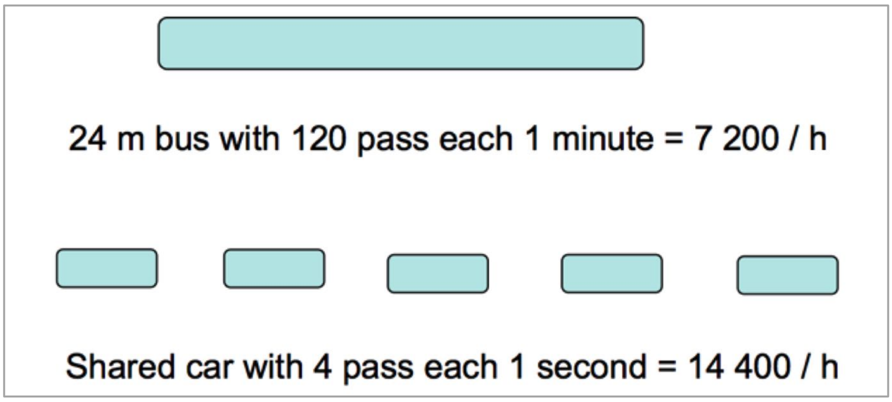


Figure 15 Cars at 1 sec headway offer twice the capacity of a 24-meter bus

On demand mobility services

The advantages of NuMo is not only line capacity in comparison with buses. While buses with a fixed route can only serve a corridor, the NuMo non-stop transport network with on-demand services can serve a wide area in all directions. In the first phase with Level 4 automation, when the vehicle leaves the NuMo network, the driver can then take control and take care of the last-mile driving. Networks also offer alternative paths to avoid congestion. In addition, on-demand service means that vehicles run only when and where needed. This is another advantage over time-tabled buses since there will be no need to run scheduled buses empty.

Ride-sharing

Privately owned autonomous cars are expected to increase travelling due to longer commutes (when commute time can be productive), more trips made (errands, sending car home to park) and diversion from public transport. All these effects contribute to more traffic (vehicle kilometers travelled).

We can reduce traffic by efficient ride-sharing and minimal empty trips. Both of these measures assume that the vehicles belong to a public fleet. Efficient deployment of a public fleet would both reduce the fleet size needed and increase road transport capacity. This section describes conditions for ride-sharing.

Simulation studies of ride-sharing strategies at KTH Centre for Traffic Research indicate that door-to-door ride-sharing can increase vehicle load by a factor of 2 [7]. Studies of PRT networks indicate average ride-sharing a factor 3 between stations during peak time. An efficient route for ride-sharing combines in real time multiple origins and destinations with limited detours. Such strategies have been developed at LogistikCentrum (PRTsim) and the French research institute Vedecom [8], applied to PRT networks and shared autonomous taxis.

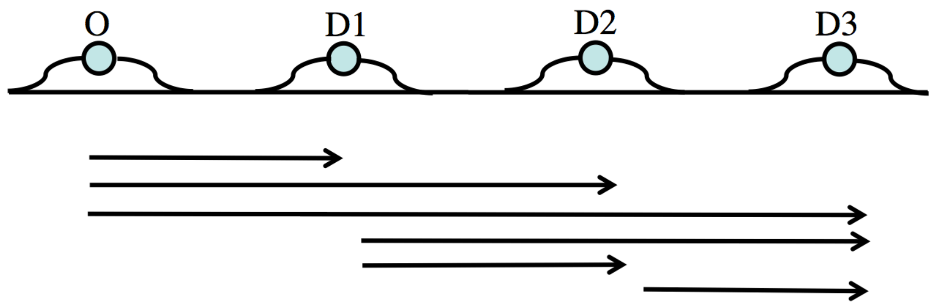


Figure 16 One vehicle with 3 destinations can serve 6 different origin-destination relations

This study assumes a public fleet of cars (or minibuses) offering shared rides between stations (taxi stands) within walking distance from trip origins and destinations. These stations must be off the main guideway or outside the dedicated network.

Since passengers' origins, destinations and departure times are very diverse, vehicles with four seats are normally large enough. But at peak times in peak directions it may be possible to fill a minibus for 6-8 passengers.

Conclusions on capacity and control

• Merge-diverge network of dedicated lanes for communicating autonomous vehicles

• Stopping only in off-line stations and outside the network

• Sensors and V2V communication enable short headways in the order of one second

• Lane capacity of small autonomous vehicles exceeds the capacity of double-articulated buses at 1-minute headway

• Intelligent traffic signals manage merge conflicts by assigning a passage time slot to each approaching vehicle

• Local sensors update vehicle-based navigators choosing network paths

• Public vehicles offer shared rides on-demand between stations

NuMo Infrastructure Integration

Building a complete network of dedicated lanes would take many years and involve a multitude of new infrastructures and changes in cityscape – some positive and some negative. A natural evolution path is to utilize the existing infrastructure such as the existing dedicated lanes for buses. New infrastructure should be also considered during the city planning with integration of future AEVs. As illustrated in Figure 17, the first stage could be to give priority to AEV such as give AEVs access to bus lanes, at traffic lights, etc. This eventually will evolve to stage 2 where dedicated networks are designed for AEVs only. This will need new infrastructure including new roads, under-ground and above-ground infrastructure.

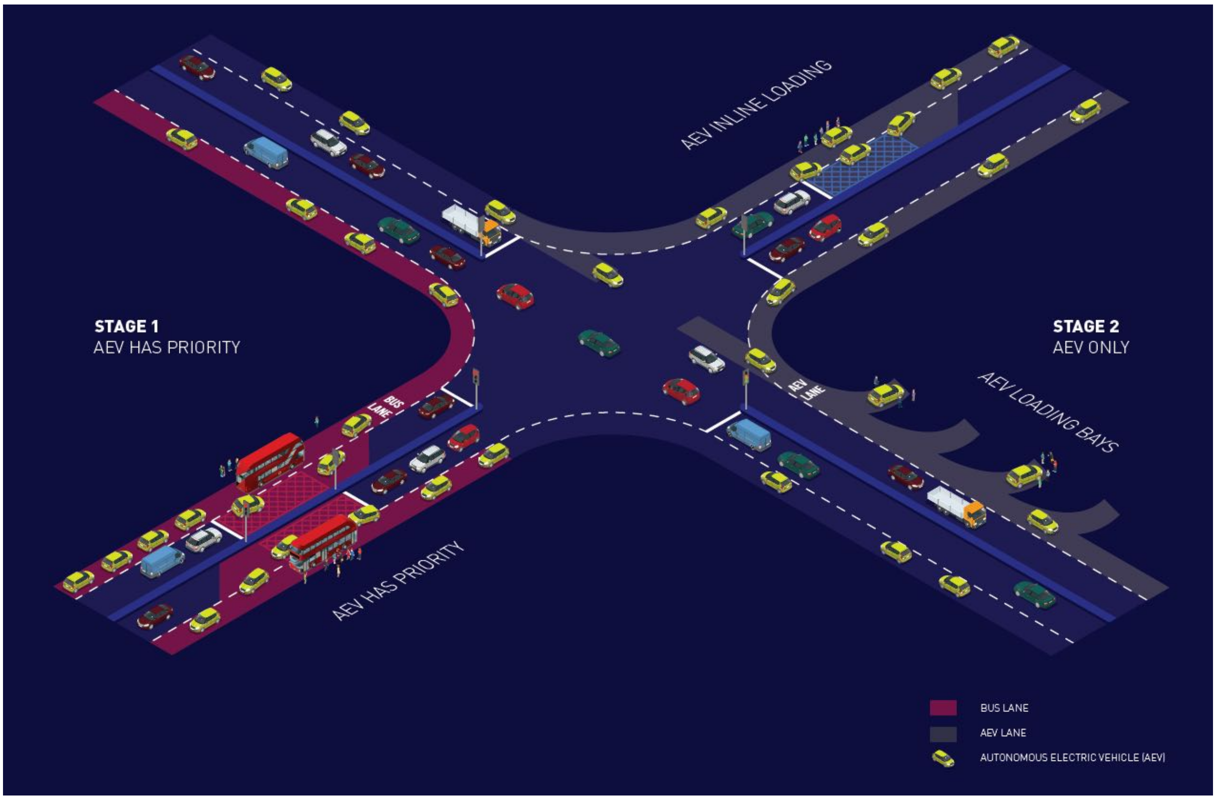


Figure 17 A potential integration path for AEV

Take advantage of existing infrastructure

Many cities already have dedicated lanes for buses and in some cases these lanes are also permitted for taxis. These lanes may not be fully connected today but they offer a low-hanging fruit for the first phase network. Connecting bus lanes to form a network would create a semi-protected environment that can be opened up for autonomous vehicles. These vehicles have sensors to stop when hindered by a bus.

In the next step all bus stops should be off line, allowing undisturbed flow of passing traffic. The capacity of bus lanes is limited to about one vehicle per minute by buses stopping on line. By introducing off-line bus stopping bays the lane capacity would be dramatically increased to about one large bus every three seconds. With bus bays we can allow other vehicles to use the bus lanes. Autonomous vehicles can co-exist with manual buses although they will have to slow down for buses exiting bus bays.

In this scenario we assume that the bus lanes in question are separated from pedestrians and other road users. If not, the autonomous vehicles would need to slow down considerably.

In places where bus bays are not possible it may be possible to overtake in the adjacent lane. Special traffic lights would stop traffic in the bypass lane, allowing bypassing autonomous vehicles to bypass a stopped bus.

Bus Rapid Transit systems (with dedicated lanes and stations at the level of bus floors) often have stations off line already in order that other buses may pass, as shown in Figure 18.

Figure 18 Example of BRT bus station (Colombia)

Finally, the buses may also be made autonomous so that they can perform controlled merges with autonomous cars and minibuses. Then all vehicle motions in the lane can be synchronized and conflicts can be regulated by smart traffic signals communicating passage time slots to each vehicle.

The need for new infrastructure

Completing the network of dedicated lanes may be facilitated by viaducts and tunnels. New dedicated links can be added at grade if there is space, above grade on purpose-built special viaducts dimensioned for narrow and light vehicles only. To keep costs down and to limit visual intrusion, many of these viaducts and tunnels would be dimensioned for small and light vehicles only. Normal big buses may not be accepted although minibuses and vans would.

Tunneling is another option below ground, under water or in the water floating or resting on the waterbed. Tunnels can be dimensioned for small vehicles only 2 x 2,5-meter envelope with footpaths for emergency evacuation.

The choice between new road lanes, viaducts or tunnels or combinations of these depends of course on local conditions. The important factor is dedicated space to offer a protected environment and controlled merging of traffic flows.

Following the principle of non-stop traffic, intersections of dedicated lanes at the same level should be avoided. Intersections with general traffic needs to be protected by signals and if needed by physical barriers.

One infrastructure for different modes

The dedicated infrastructure can be made available for different kinds of vehicles and users as long as they are able to avoid collisions, communicate and maneuver to meet passage time slots. We also assume that all vehicles in tunnels must be exhaust-free (electric with battery or hydrogen and fuel-cell). The following modes are foreseen:

- **Public transport with shared autonomous taxis and minibuses**. Dedicated stations where people wait to be picked up and dropped off. Ride-sharing is assumed in public vehicles. Fares may be subsidized and integrated with conventional transit fares.
- **Private cars and shared cars**. As long as they meet performance requirements, they are accepted against a user fee. The fee may include electric on-road charging as range extenders for battery cars. The fee can depend on level of congestion, time-of-day and distance travelled. The revenues from private cars can be used to subsidize public transport in the network.
- **Delivery vans** which meet the performance requirements and are not too big or too heavy.

Integration with public transport

The network of dedicated lanes is planned for a public transport system on-demand and non-stop between stations. The vehicles can be taxi cars or mini buses depending on expected demand and ride-sharing strategies. This public system should be integrated with conventional public transport with a common fare structure (same passes and tickets and free transfers).

Shown in Figure 19, the most efficient interchange between NuMo and a Metro is a cross-platform interchange. The difference between a metro and NuMo is that passengers in the metro are unsorted in regard to destination, while the NuMo passengers are sorted by destination.

Thanks to the integration with public transport the on-demand system can be made to feed to existing mass transit nodes. If passengers want to go to other addresses than transit stations, they may have to pay a higher non-subsidized fare. The same vehicles may also pick up anywhere for door-to-door transport as a commercial (driverless) taxi fleet with a commercial fare.

Figure 19 Illustration how NuMo integrates with a Metro

Depending on political decisions the network may or may not accept different categories of fleets including public transport, taxi transport, goods deliveries and private cars. From the service perspective, the same vehicle technology and even the same vehicle may provide different services at different times.

Policy decisions play an important role. They set road charge and subsidies for various modes. These charges may depend on time of day, zone and distance travelled. The policies can also require that only electric vehicles are allowed in tunnels or in the whole network. Those questions will need further investigation for a proper implementation.

Charging of electric vehicles

New infrastructure can offer charging on the run by induction or sliding contacts. Car batteries can then be dimensioned smaller and lighter and still offering good range. The cars in the NuMo system would in this case not need to stop for the driver to rest but also not need to stop to refuel. The same toll collection system can incorporate the price of electric energy. The charging system would be an additional source of revenue for the owner of the infrastructure. Further investigation should be done together with the on-going electric roads test and pilot projects.

Infrastructure access control and interaction

As soon as buses have been made autonomous, manually driven vehicles would not be permitted in the dedicated network. This is a prerequisite for high capacity, smooth traffic flow and safety.

Entry points to the dedicated network will have a communication exchange with approaching vehicles. Vehicles have to verify their performance and communication capabilities. The transfer between conventional and dedicated space will be simple lane-change with no physical barriers. Non-conforming vehicles will be warned and barred from entrance. Geofencing technologies that embeds digital traffic rules for vehicle control has been tested in Sweden[12] and has been implemented in Gothenburg on bus line 55[13]. A working plan [9] is also published to further integrate and apply the technologies in the Swedish society.

[12] http://bit.ly/trv-geofencing
[13] https://www.svt.se/nyheter/lokalt/vast/bussens-hastighet-styrs-med-gps-signaler

Remaining at-grade intersections with other traffic would be strictly signal controlled. Non-autonomous vehicles would otherwise require longer safe distances.

Dealing with vehicle breakdowns

At grade it is sometimes possible to overtake by changing lane or using a road shoulder. Dedicated and separated lanes may hinder overtaking, especially for elevated guideways and in tunnels.

In tunnels, only electric vehicles are permitted for reasons of ventilation. Even at grade and elevated, more and more of the vehicles are expected to be electric. Electric vehicles have much fewer moving parts and a lower risk of failure. Before entering the dedicated network, the charge level will be verified to be sufficient throughout the network or at least to the given destination with some margin to avoid potential running out of battery.

Vehicle failures are still possible e.g. due to a broken wheel axle, bearing, steering or suspension. When this happens other vehicles' paths are diverted to avoid the blocked link through e.g., C-ITS networks. Only vehicles behind on the same link are hindered until the broken vehicle can be removed.

Vehicles at grade and above grade can be removed by way of cranes or rescue vehicles. A broken vehicle in a tunnel can either be pushed by the vehicle behind or pulled by the vehicle in front. It is possible that all autonomous vehicles will be equipped with bumpers to push another vehicle at creep speed.

If pushing does not succeed to remove the broken vehicle it can be pulled by a rescue vehicle backing in on the cleared link in front of the broken vehicle. This method should work everywhere and may be the standard procedure. The rescue vehicle can even lift the front of the broken vehicle if needed.

Impacts

Autonomous and electric vehicles, together with new business models such as ride sharing will transform the future mobility. Urban cities are embracing the transformation for future sustainable cities where the infrastructure will accommodate the AEVs for maximizing impact. This transformation process will have significant impact on the car industry and cities.

Impact on the car industry

Volvo Car have recently declared that full autonomy (SAE Level 5) may be 15 years off. A dedicated and semi-protected infrastructure offers a controlled environment with less challenges (pedestrians, children, dogs, bicycles, intersections, left turns etc.). We have already seen vehicles such as 2getthere (Figure 20 left) and Navya (Figure 20 right) capable of safely operating in such a controlled environment.

A dedicated infrastructure enables early deployment (SAE Level 4) for industry to demonstrate and validate their technology. This would enable a car manufacturer to stay on the forefront and start scaling up production with an income stream.

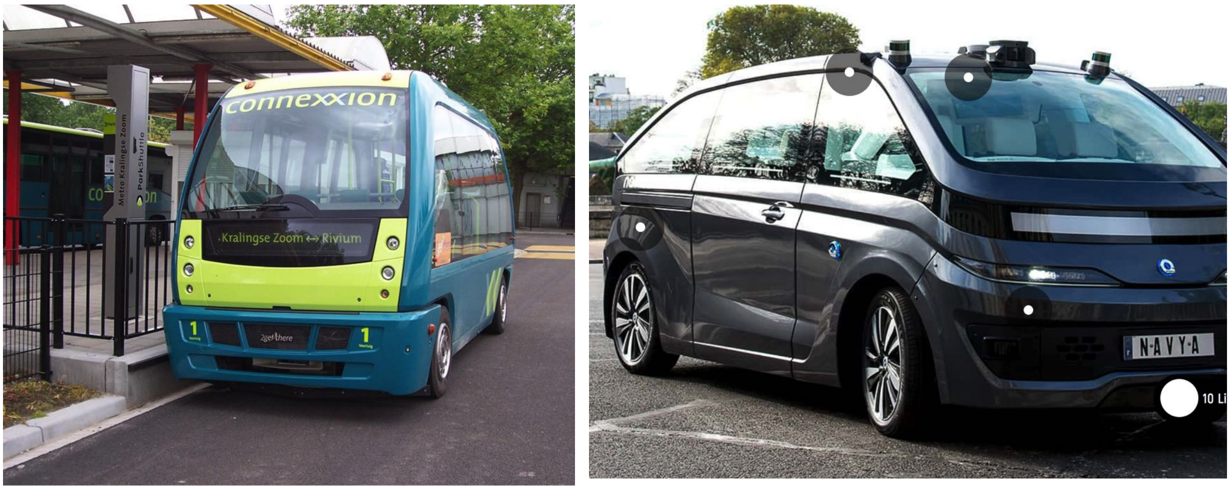


Figure 20 2getthere driverless Rivium Park Shuttle in Rotterdam since 1999 (left), Navya Autonomous Cab (right)

Impact on cities

Many cities are under pressure from increasing traffic and congestion. The introduction of autonomous cars on the existing road network is expected to increase traffic by longer commutes, more trips, empty trips and diversion from public transportation. New infrastructure may alleviate the negative effects in several ways.

Existing bus lanes will be able to accommodate more traffic when stops are off line and even more so when all vehicles in these lanes are autonomous.

When new infrastructure is needed it can be designed for small autonomous vehicles only. Hence less cost, less visual intrusion and less space required. The existing infrastructure then can accommodate more heavy traffic.

With new infrastructure above and below ground, some of the existing road space may be converted to other uses or to other modes of traffic (pedestrians and bicycles). In addition, tunnels can overcome barriers such as water, parks and historic areas.

The location of a new dedicated road network will depend on the city environment and its opportunities for novel infrastructure. Sometimes existing infrastructure can be converted – such as urban motorways and segregated bus lanes. Sometimes short pieces of new infrastructure may be sufficient – such as short fly-overs or underpasses past complex intersections. In many cities however the NuMo system may offer a viable alternative to new expensive metro systems.

The choice between above grade systems and tunneling will be defined by local considerations – the current environment, its values such as nature or historical or a general preference for having visible or not visible infrastructure. In the future cities may prefer that transport infrastructure is generally hidden from sight and city streets be given over to pedestrians and bicyclists.

As shown in Figure 21, the dual lane means that NuMo vehicles can load and unload at stops while other NuMo vehicles continue past without stopping. Access to the NuMo stops are part of the street layout with various possibilities for imaginative integration in the street scene, ranging from simple ramps and stairs to refashioning the streetscape entirely.

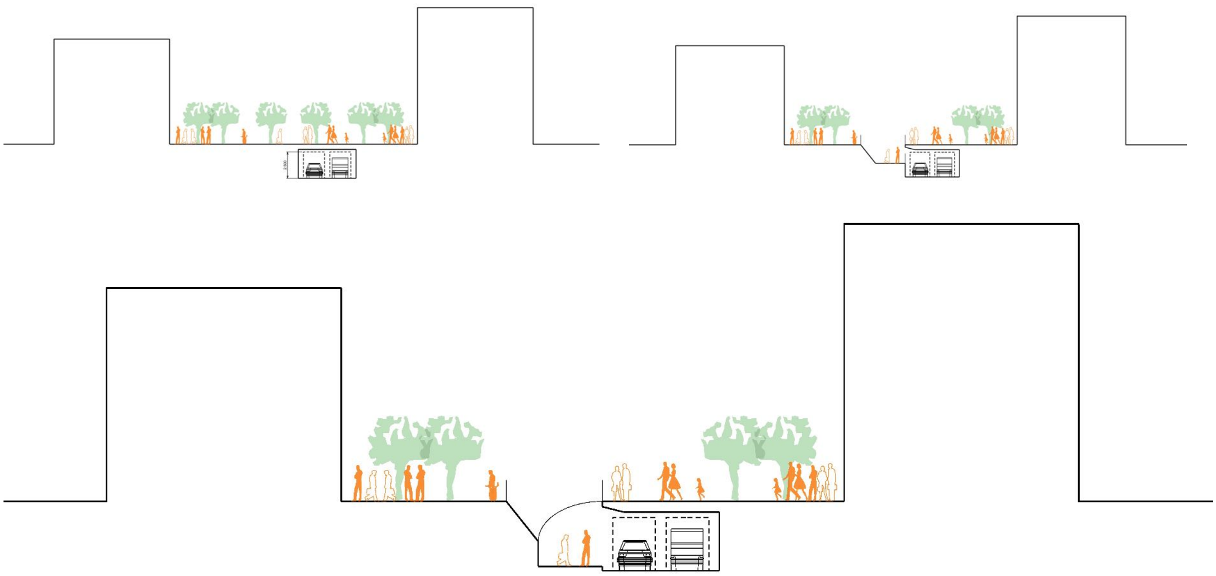


Figure 21 Typical cut and cover of NuMo system

Role of politics

To integrate the autonomous vehicles into traffic systems and to maximize the impact on transport, society and environment, strong political involvement is essential to facilitate the process. While autonomous vehicle development falls into the hands of vehicle manufactures, implementation and use of new infrastructure remain under political control.

Public transport would be a priority user offering on-demand and non-stop transport feeding existing mass transport hubs. Public transport may benefit from cross-subsidies based on road tolls paid by private users.

Ride-sharing strategies is applied to the public transport, so that on-demand transport can be combined with higher vehicle loads, especially during peak hours.

Limiting access to the new infrastructure to zero-emission vehicles is expected to speed up the introduction of such vehicles, with consequential benefits to air quality and climate effects.

Case illustrations

NuMo represents the future mobility concepts and incorporates the forthcoming AEVs, new infrastructure concepts, digitalization, as well as new business models. While we provide design principles and potential solutions of NuMo, implementation needs to closely connect with local situations such as geographical characteristics, local infrastructure and policies, etc. We take the city of Stockholm and Gothenburg as two cities from Sweden for quick illustrations.

The city of Stockholm

Stockholm has a particular relationship to water. It rose as a city connecting water with land. In the last century the preponderance of land-based transport (roads and rail) meant the city expanded north and south. Water was regarded as obstructions to be overcome and resulted in very large bridge and tunnel civil engineering – a trend that continues to be reflected in today's strategic plans.

An alternative would be to regard the water as an asset for transportation. It is clear that the water itself must be retained. However, tunnels under water either anchored to sea bed or in deep waters floating as has been proposed in Norway as part of the Norwegian E39 Coastal Highway Route[14]. The submerged tunnels would offer a very different strategic choice for the further development of Stockholm, as shown in Figure 22 the concept illustration.

Figure 22 Submerged tunnels in Stockholm

Figure 23 illustrates a simple exploration of floating / sunken tunnels in Stockholm. The NuMo system connects to existing motorways where it is assumed a lane will be set aside for NuMo vehicles. It also proposes repurposing one existing lane of urban motorway (Söderleden) and bus lanes for inner city distribution.

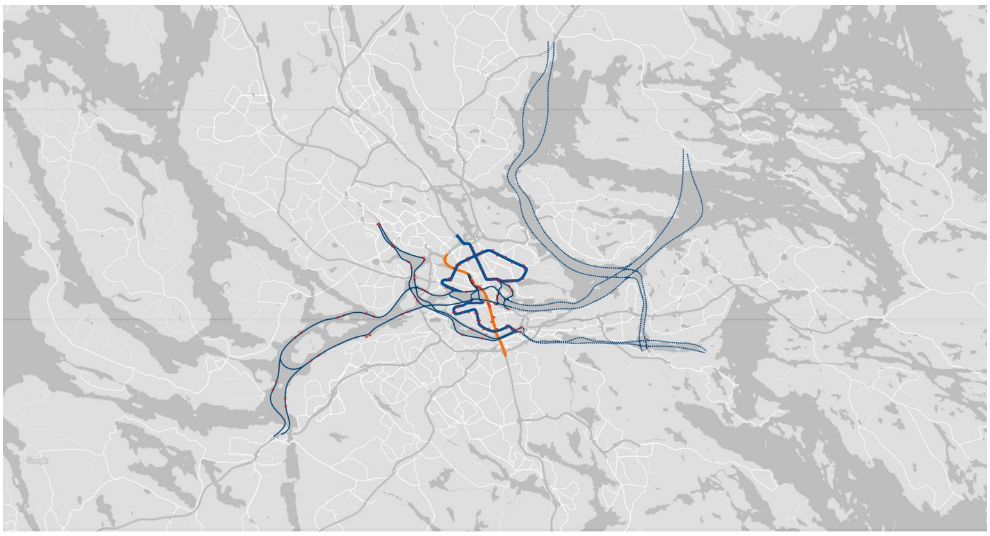


Figure 23 Example of sunken / floating tunnels map

[14] https://www.vegvesen.no/en/roads/Roads+and+bridges/Road+projects/e39coastalhighwayroute

It is unlikely that such a system would be built from scratch so there is a strategy for gradual introduction of the system. The idea is to convert some existing infrastructure such as the Söderleden motorway and combine that with a conversion of existing bus lanes to take NuMo traffic. Figure 24 shows one example where the NuMo system also connects to existing motorways where it is assumed a lane will be set aside for NuMo vehicles.

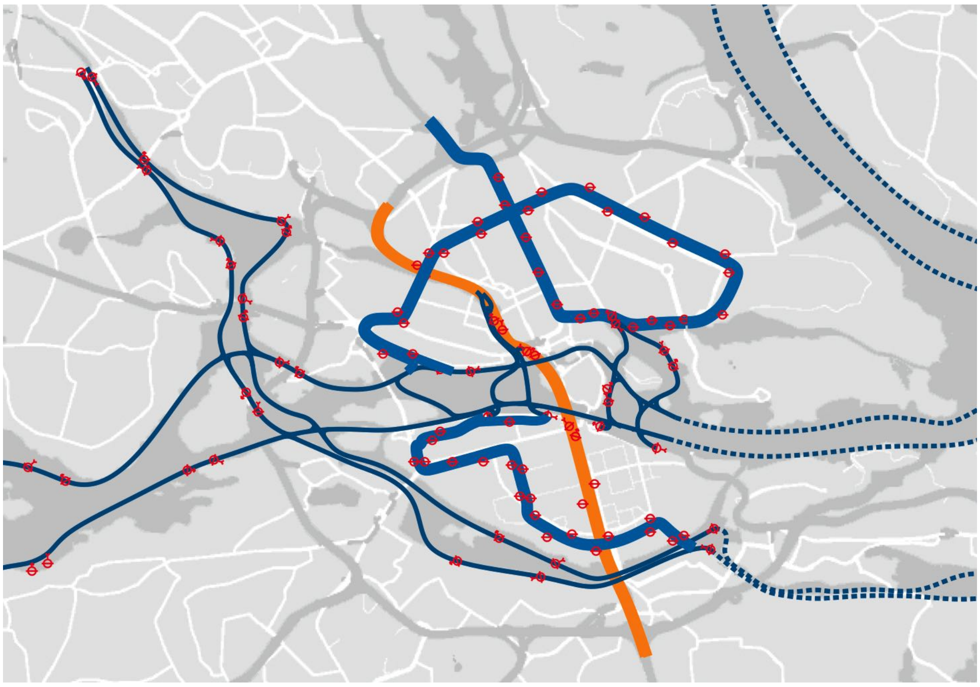


Figure 24 Example to integrate of NuMo with existing infrastructure

Introducing NuMo will expand the 30-minutes travel zones in Stockholom. Figure 25 illustrates the current travel zones within 30 minutes. Assuming an average speed of 50 km/h, the 30minute travel zone can be enlarged significantly, as shown in Figure 26. The 50 km/h average speed is based on 80 km/h in the underwater tunnels with a much lower speed (at around 30 km/h) for the local distribution on existing (or new) roads, combining to give an average speed of 50 km/h for the system as a whole.

Figure 25 Current area accessible within 30 minutes [15]

Figure 26 Increased access areas with NuMo

[15] http://www.mapnificent.net

The city of Gothenburg

The Lindholmen area in Göteborg is a growing centre for engineering science and research on autonomous transport. Public transportation to the area is oversaturated. Dedicated space is provided for buses throughout the north river bank Lindholmsallén.

The Lindholmen area is separated from the city center by the Göta Älv river with limited connections across the water.

Figure 27 illustrates how NuMo takes advantage of both available infrastructure and potential new infrastructure. Shown with the red lines, the dedicated bus lanes could be better utilized with autonomous shared taxis to offer on-demand mobility services thus increasing the road capacity and traveling convenience.

For better connection between the two sides of the river, two tunnels are designed for small vehicles as shown in the figure with straight blue lines, the lower tunnel is a single lane tunnel and the upper one is a double-lane tunnel. The blue circles indicate a walking radius of 300 meters around each station.

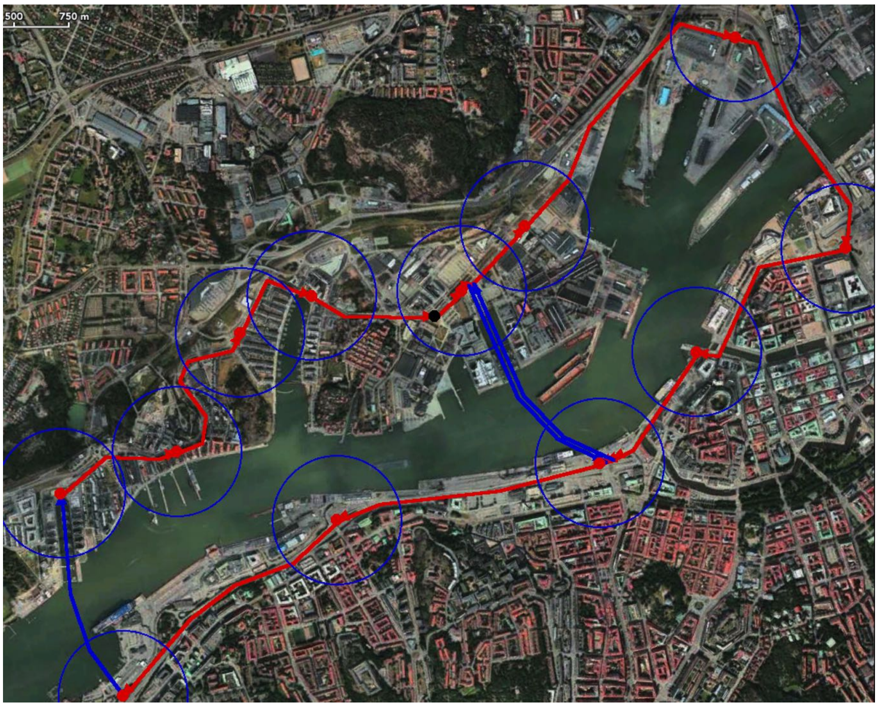


Figure 27 NuMo takes accounts of both existing infrastructure and new infrastructure

Wider opportunities – London

The early case study of NuMo, i.e., the CarTube[16] of London, illustrates the potential revolution an underground type system can bring. A new underground system would require very large systemic advantages to be acceptable. The London example is designed to illustrate this point. Unlike the existing Underground (Tube) system NuMo is a switched network allowing any vehicle uninterrupted travel to its destination.

[16] We acknowledge that Cartube is an early version of NuMo, and in this Section it means the same concept with NuMo. For more detailed information on Cartube, please refer to www.cartube.global.

Design

The topology is based on a 3 x 3 grid with each square 1.5 km, giving 6 sets of tunnels east west and north south, as shown in Figure 28.

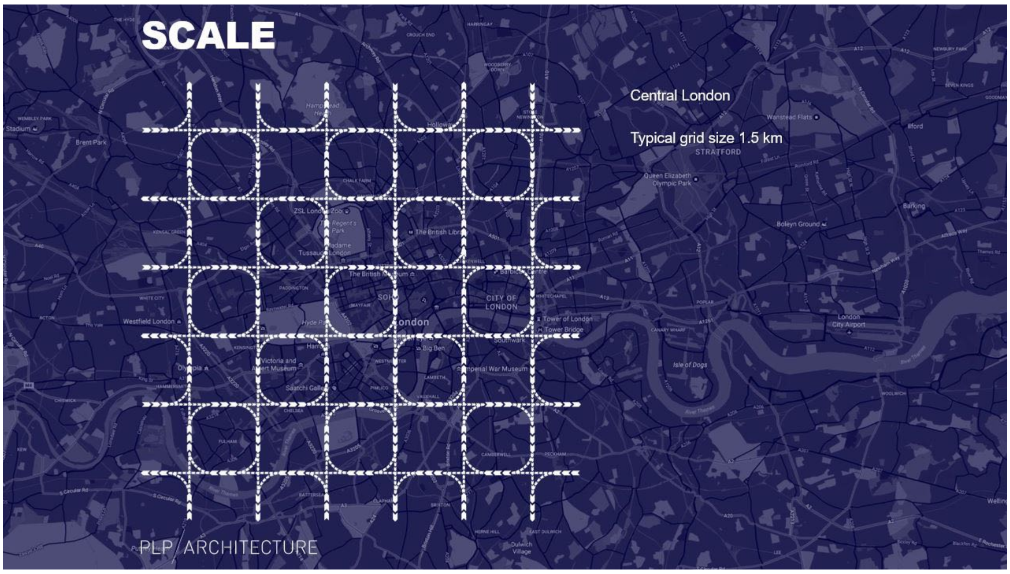


Figure 28 Potential NuMo network in London

Just as with extensions to the London Underground system the system depends on existing feeder systems. In the case of cars this system is naturally the motorways (shown in Figure 29), which could easily be converted to autonomous vehicles, even in a staged fashion with an initial lane set aside for NuMo vehicles. Unlike the railway system which Crossrail 1 and Crossrail 2 use as feeders these infrastructures are modern and likely to be maintained and developed with the advent of AEV's.

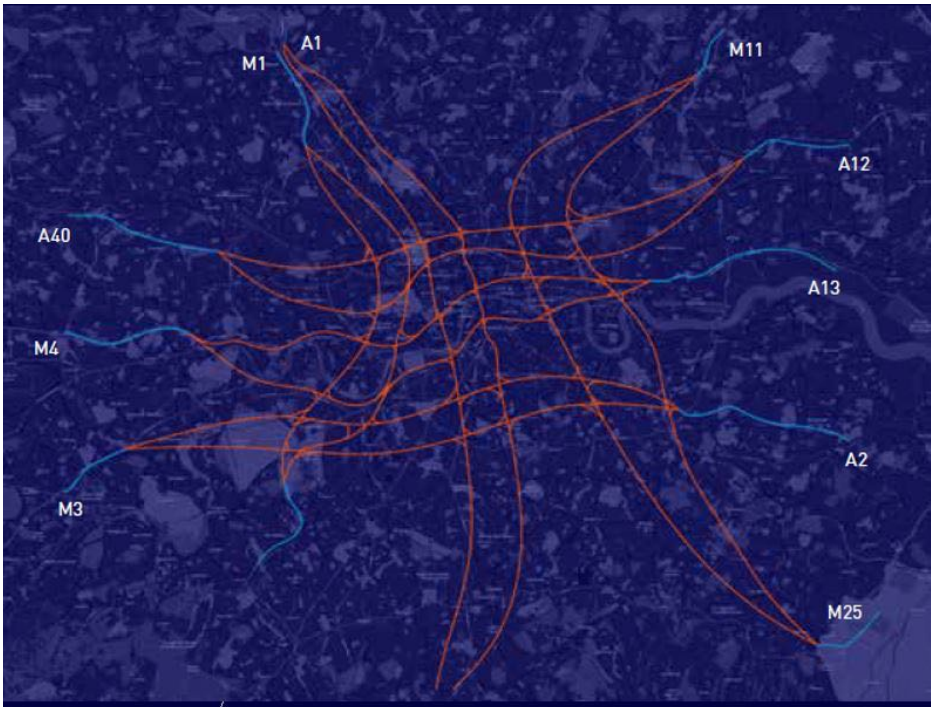


Figure 29 Connecting the urban NuMo network with highway networks for road network extension.

Capacity

It is interesting to compare the capacity of such a system with existing Underground system.

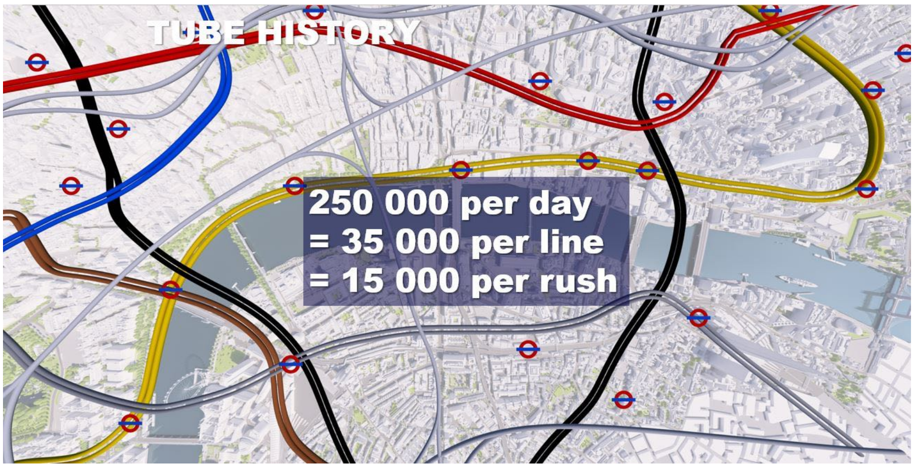


Figure 30 Current London tube capacity

Looking at Central London the Underground (Figure 30) delivers about 35,000 passengers per line into central London, a total of about 250,000 people. More arrive by train to feed the total City workforce which is approximately 300,000. At rush hour the system is extremly overcrowded.

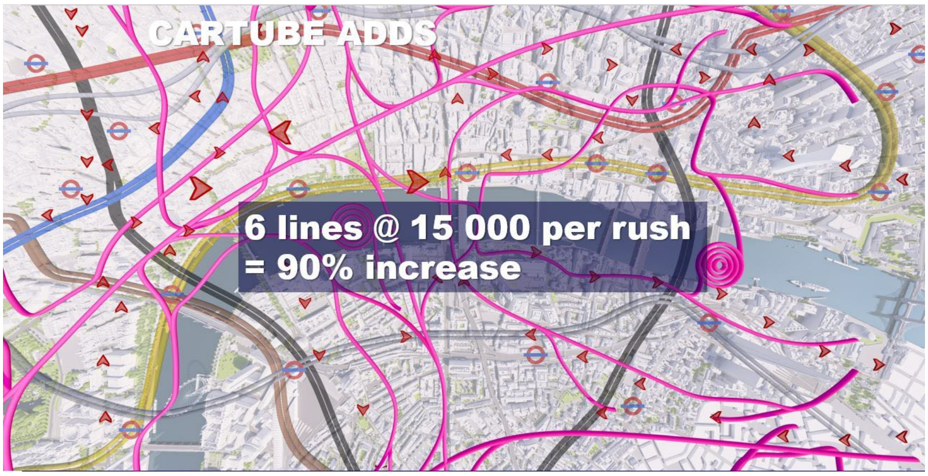


Figure 31 NuMo potentially can double the capacity of London traffic

With introduction of Cartube network of 6 lines and a total capacity of 15,000 per rush hour per line, the commuting capacity could nearly be dubled.

Exits

The CarTube using smaller tunnels and being a switched system could have more outlets than the current Underground. The location of stops becomes the important factor, not the layout of the system since the switched system ensures noboby needs to know or care about the precise path to the stop.

Lookead at it this way the thing that matters is the density and number of stops. The more stops the shorter the final walking distances. The CarTube layout aims to have a density of stops approaching that of normal bus stops.

Figure 32 Cartube exits could have a similar density of bus stops

Despit of the benefits of such a system, we acknoledge that the London is seen mostly as a thought experiment and concept illustration. It is unlikely such a system would be implemented in an existing complex city such as London.

Wider opportunities – New York

If the NuMo concept becomes the foundation of modern urban transport the implication, particularly if combined with floating tunnels, will be huge. Cities will reuse their old port facilities into gateways for modern transport and can rethink the strategic direction of their growth.

In New York the constraints of the Hudson and East Rivers could be turned into huge new opportunities. Figure 33 illustrates how NuMo could be introduced with new infrastructure and with existing infrastructure.

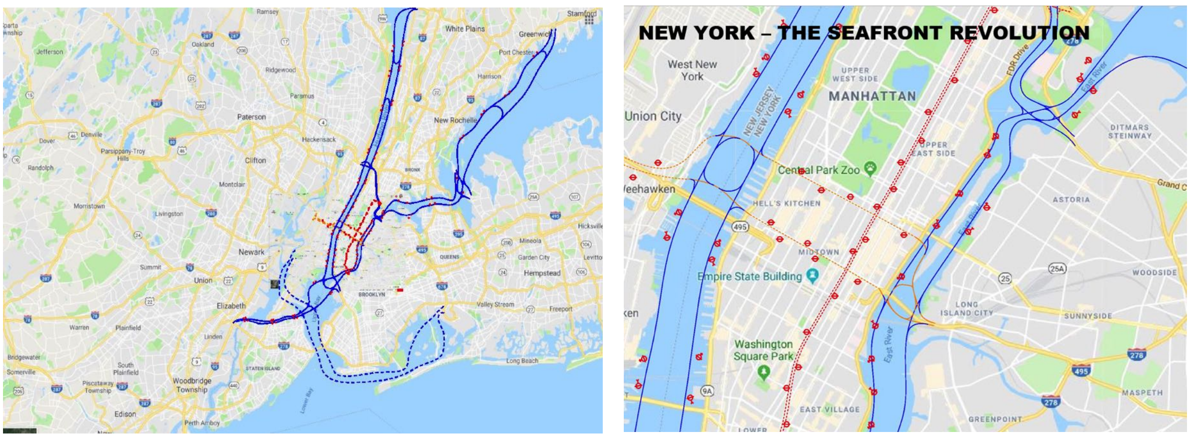


Figure 33 The local layout could incorporate the reuse of existing infrastructure or the introduction of new infrastructure

As shown in Figure 34, with NuMo, the difference in travelling times would be dramatic, the half-hour travel zone will be expanded significantly.

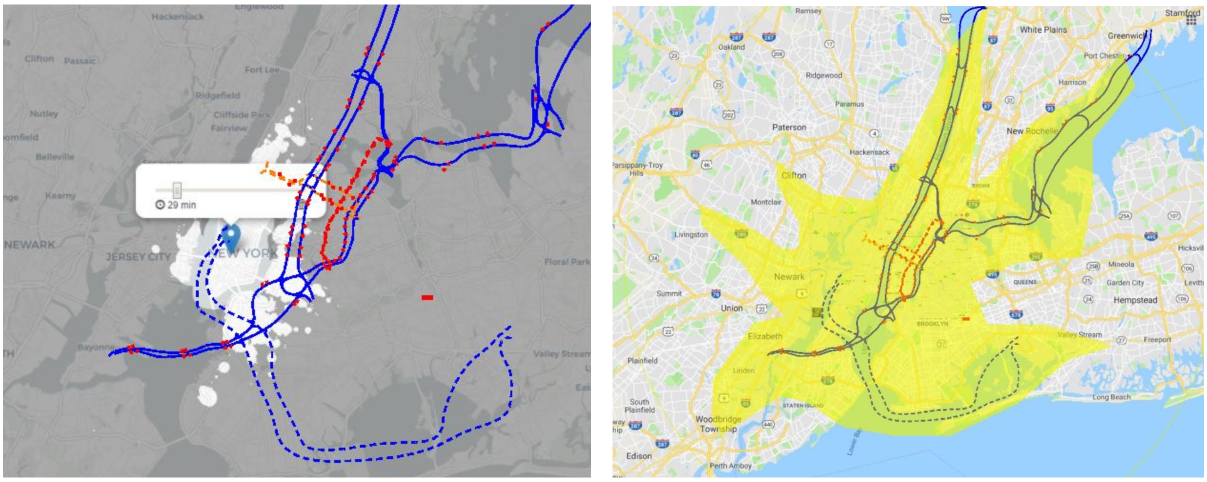


Figure 34 Travel zones within half an hour, today (left), with NuMo (right)

NuMo Infrastructure Construction

NuMo is an evolving transport system which at its early stage will mostly be based on available infrastructure. During the transition, new infrastructure will gradually be needed to connect existing NuMo system to a fully connected and dedicated transport network. In this chapter, we illustrate the potential new infrastructure alternatives of NuMo and discuses in general the construction requirements and methods. We give very brief discussion on the topic here and refer interested readers to Appendix: Infrastructure Construction for more detailed discussion and references.

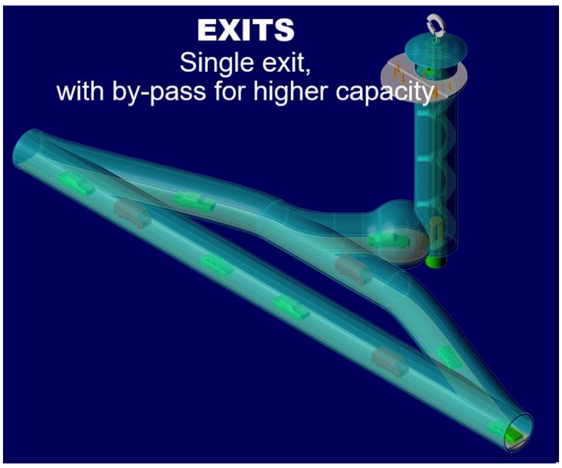
Infrastructure alternatives

For such purposes, it is foreseeable that there will be different alternatives for NuMo including underground, above ground, as well as submerged tunnels, as already shown in previous chapters.

Underground systems

NuMo tunnel construction will be similar to other type of tunnels while the biggest difference is the size. Since NuMo is built for urban passenger mobility, the size of the tunnel will be smaller and that will affect significantly the construction costs. As recently claimed by Elon Musk, the boring company tunnel could cost $10 million per mile[17]. Though the detailed cost analysis for NuMo is yet to be done, it is expected the cost will be much lower than traditional ones. As for construction details, we refer readers to the Appendix: Infrastructure Construction.

Another major construction regarding underground network is the stop exit construction. The stop exit designs will vary with demand and local conditions. Their size will vary from single vehicles to large installations coping with 50+ AEV's simultaneously, and this allows stops to rival the capacity of an Underground station.



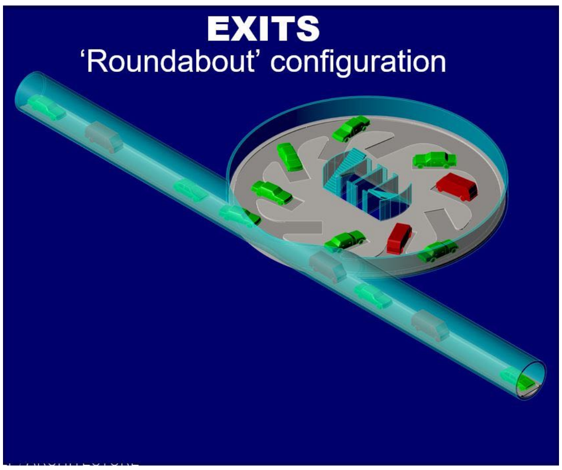


Figure 35 Potential construction alternatives of NuMo exits for passengers and for underground car park

[17] http://bit.ly/boring_tunnel

The system would also integrate with existing transport systems where appropriate. In the case of existing railway stations and platforms a direct lift to the CarTube is envisaged.

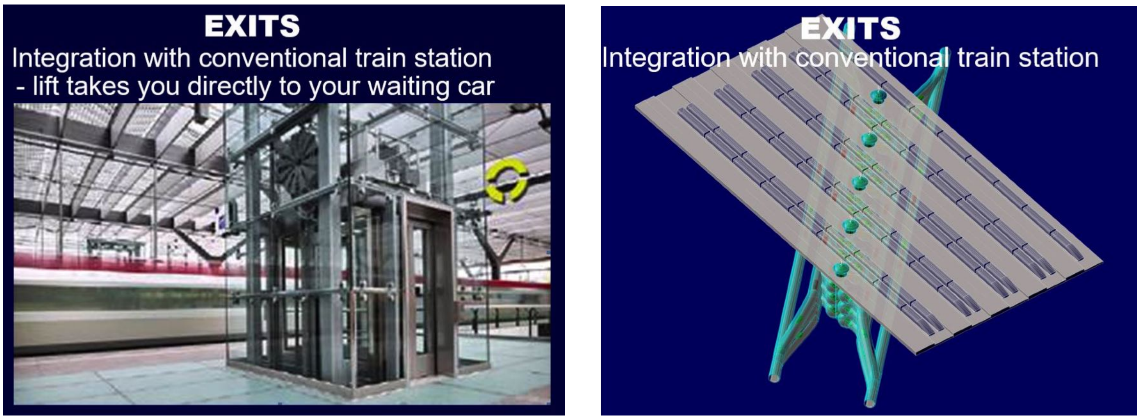


Figure 36 NuMo exits with conventional train stations

Existing roads can also serve as a 'last-mile' delivery option where vehicles eamlessly emerge onto the existing street system and the AEV delivers passengers and goods directly to individual properties. These exits would be similar to existing tram tunnel entrances.

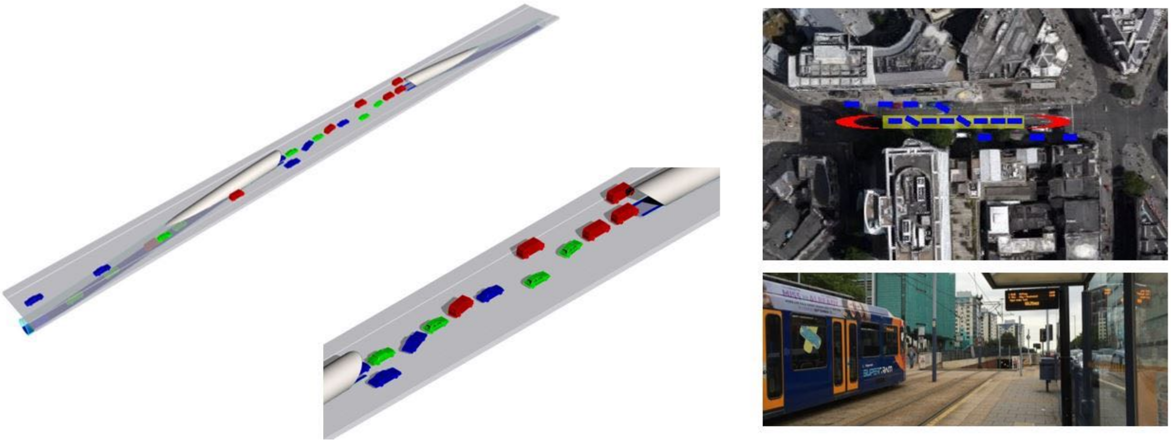


Figure 37 NuMo exits with existing road systems

Above ground systems

Conceptually above ground systems are very similar to below ground systems. Naturally systems can be mixed with portions above ground where appropriate. Construction costs of above ground portion of the system would be substantially cheaper than underground parts.

The big advantage of NuMo above ground is that the imposed load is less than a normal pedestrian bridge allowing fewer substantial structures. One design alternative is shown in Figure 38.

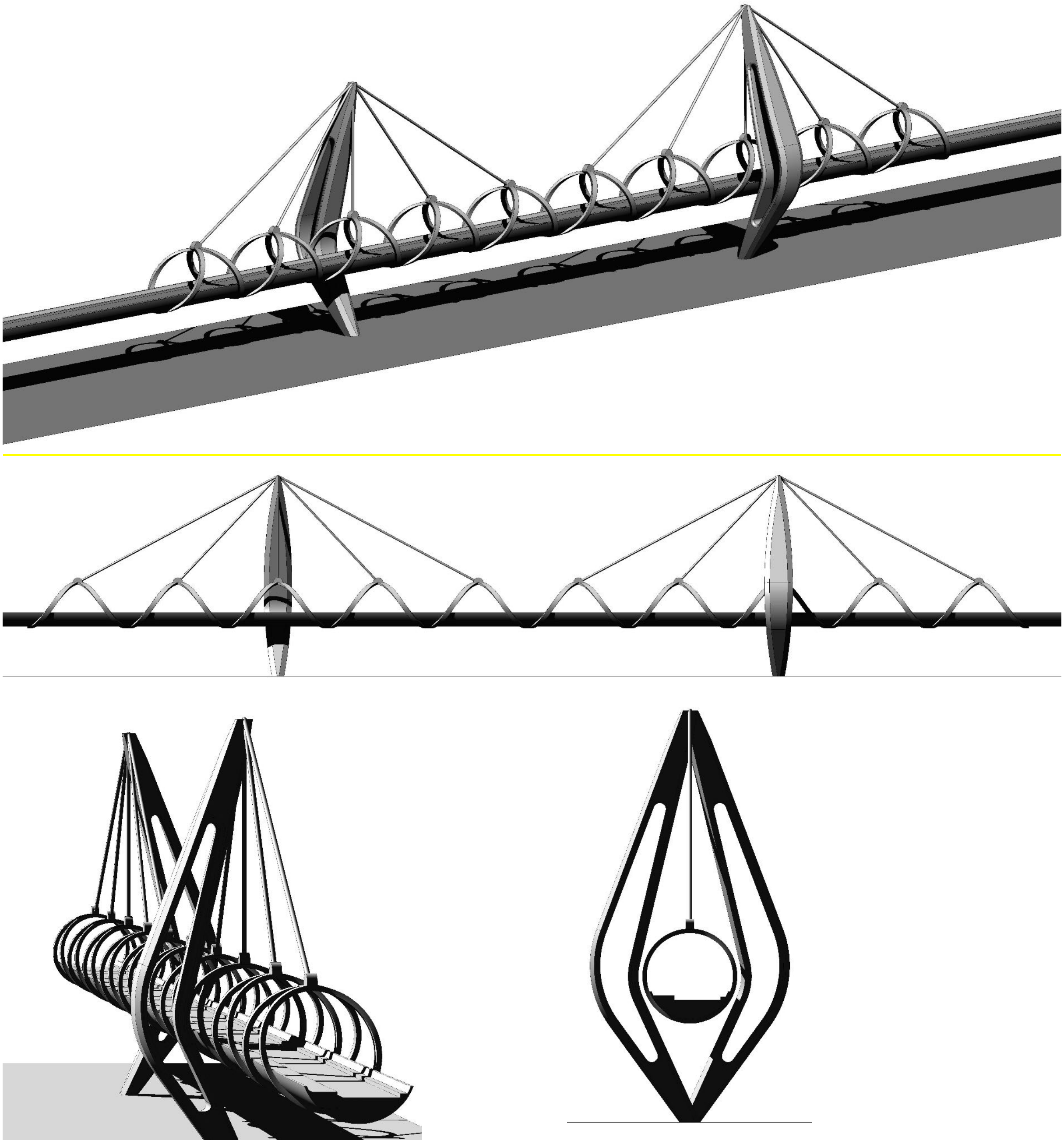


Figure 38 Potential NuMo above-ground infrastructure

In addition there are opportunities to integrate above ground structures with buildings and streets as shown in Figure 39, but with better design solutions than conventional high-level urban mass transport.

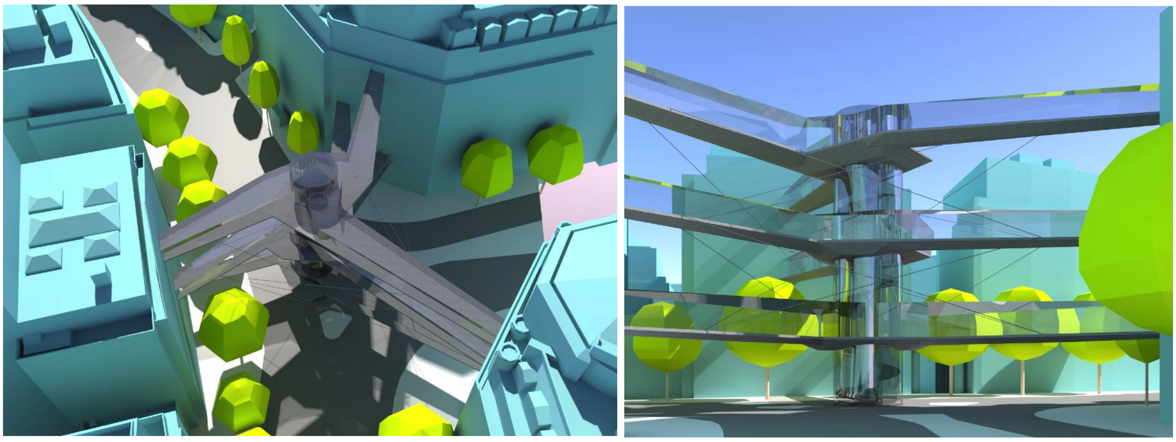


Figure 39 NuMo integration with urban buildings

Submerged tunnels

Tunnels under or even floating in water are an exciting opportunity to rethink urban strategies as shown in the case studies about Stockholm and New York. While this is under investigation in countries with many lakes such as Norway, large cities are predominantly located by water may rethink the role of water in the urban fabric and seek underwater transport for urban traffic.

Figure 40 Illustration of submerged tunnels

General aspects related to construction

The construction of new urban systems must follow the general codes for constructing and for safety. This applies in particular for transport systems, which consist of autonomously operated vehicles. Even if the system allows a smarter design with smaller and lighter building components and cross sections, redundant measures need to be in place, which allow users of the systems to escape in case of an emergency in a safe way.

Construction of above ground systems encompasses the existing or new ground level roads as well as elevated road systems. Ground level roads could be built with existing technology with addition of further installations such as communication lines/hubs, inductive charging stripes or charging stations and additional information and emergency systems. For elevated roads the size and load of the system should be adjusted to the actual needs: E.g. only one lane for each direction taking into account escape routes and exit stairs/emergency slides. Above ground systems have the advantage that in part existing road lines can be utilized for on or above ground constructions.

Construction of underground systems are more challenging concerning realization and costs. Tunnels need to be constructed by trenching/cut and cover or without trenches. The latter construction technique is required, when the already existing building density does not allow trenching. However, the cut and cover technique can be useful for exit and entry points of the system Tunnel construction techniques for passing vehicles can be done by the drill and blast technique or by tunnel boring machines (TBM) of different sizes. This includes also micro tunneling techniques (microtunneling) for smaller diameters, which are bored with similar machines as large tunnels. Both construction types have their advantages and disadvantages. TBMs tunnel continuously, where the tunnel lining is applied directly after the bulk head of the machine. When applying TBMs the tunnel cross section needs to be round. The drill and blast technique leave theoretically more options for cross section geometries, except that a vault shaped cross section is more suitable to withstand the pressure from the ground above.

Infrastructure construction needs to follow certain international and national requirements. In Europe, the Eurocodes specifies general requirements concerning structural health and safety. While at a country level such as in Sweden, many requirements concerning materials and technical solutions are regulated in the AMA Anläggning document (Allmän material- och arbetsbeskrivning – Anläggning) [10]. Similarly in Germany the road administration defined specific requirements for planning, construction and maintenance of roads and road structures (tunnels, bridges) [11].

Road infrastructure systems are one of the most expensive built structures we have. They must be safe, durable, functional and flexible to accommodate future needs. The construction and maintenance of such systems consumes large amounts of money, which often derives partially or entirely from public funding. The amount of materials used for the construction project of an infrastructure system can be enormous and the daily load can be, depending on traffic density, deleterious to the system, requiring frequent and costly maintenance. This applies in particular to road pavements but also to structural materials used for tunnels and bridges. In addition, a new infrastructure system needs to be safe and economic. This does not exclude solutions, which incorporate the application of different structural and non-structural materials. However, a designer of the system needs to balance between its size, expected service-life, sustainability towards environmental impact and maintenance and its costs. In this regard, concrete is often the choice as a structural material for below and above ground systems, because it is inexpensive, is readily available in most countries, has a good service life record and is sustainable over a long service life. For more detailed discussion on materials, we refer to the Appendix: Infrastructure Construction where some structural materials are listed with possible advantages and drawbacks. In addition, readers can also find different infrastructure construction alternatives and considerations in the appendix.

NuMo environmental impacts and sustainability

The environmental effect of NuMo is mainly related to energy consumption from the cars, wear particles and noise. On top of this, the construction phase of the system can give several different impacts, and different types of constructions, e.g. including electrical road possibilities or new tunnels or overpasses, would have different impacts. The ultimate goal of NuMo is an exhaust-free, non-stop, high-capacity mobility system that has minimized negative environmental impacts and maximized sustainability, where the city lands are returned to citizens for e.g., walking, cycling, as illustrated in Figure 41 NuMo returns city lands from vehicles to citizens.

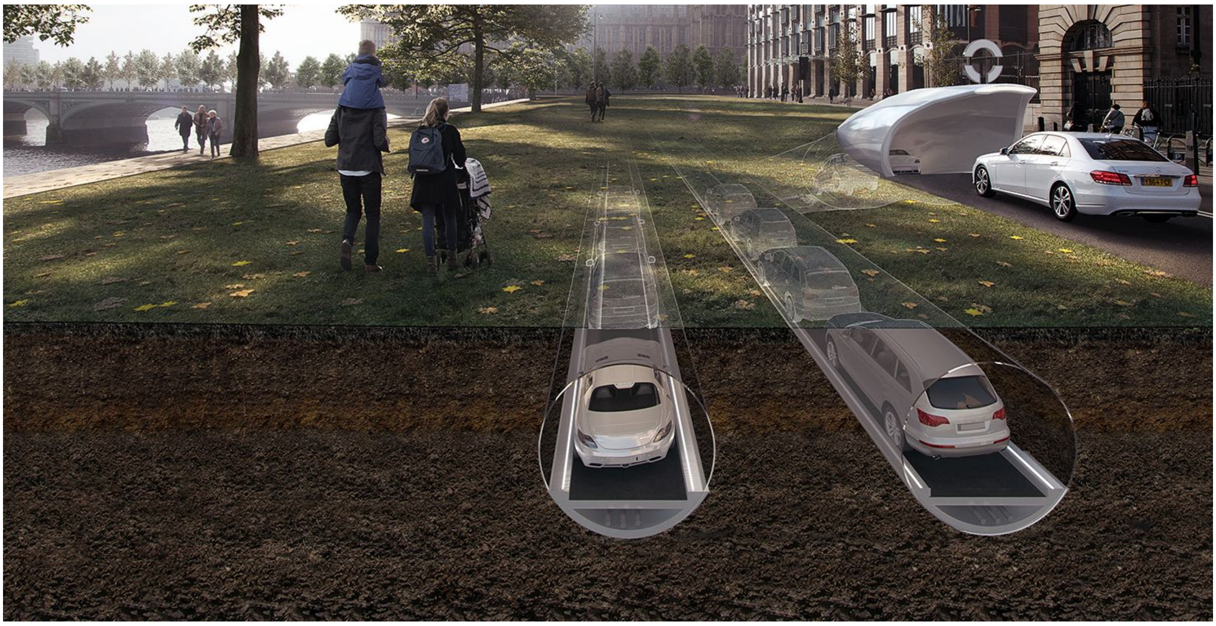


Figure 41 NuMo returns city lands from vehicles to citizens

Energy consumption

Energy consumption by vehicles is related to efficiency as well as vehicle speed, and even more to acceleration. Thus, energy consumption needs to be calculated by a sophisticated model (e.g. VETO or PHEM [12]) to show the benefits of the constant speed that is used in NuMo. These models calculate the energy need from driving cycles and all energy dissipation in the engine and energy transmission. The mainly constant speed that is assumed to be an important benefit of the NuMo system, together with the possibility to reduce air resistance using platooning, will thus be quantified as energy efficiency. If other fuels than electricity are used, the PHEM model can calculate emissions of air pollutants as well.

The emissions, including energy need, are in many models related to a measured driving cycle describing the driving behaviour of that specific road type. These driving cycles would need to be updated by the automated driving in a NuMo system, for the emission factors in the models to give low enough emissions for the constant speed NuMo system.

The energy consumption is often related to emissions of both air pollutants and climate emissions from electricity production, and to exhaust if e.g. combustion engines are used. At this stage the focus is not on the specific fuel used by the vehicles.

Impact of construction

The construction of the system will contribute with emissions that differ between different constructions of the system. The demand of energy and resources will be lower for a NuMo overpass or tunnel than for the same system if constructed for all kinds of vehicles as is common today. Important differences between building a road and a tunnel is the amount of material and working machinery, as can be seen in the chapter about Construction. Construction of the system also affects the local environment during the construction period. The National Road and Transport Administration (Trafikverket) has formed tools to facilitate calculation both of the carbon dioxide balance (klimatkalkyl [13]) and other sustainability variables (SEB[18] and SUNRA). These systems would be beneficial to use in further studies in climate and environmental impact of NuMo, as all numbers given to the tools mentioned above (mass of concrete and asphalt, mass of stone material, hours of digging etc) can give some insight into the effect on both climate and environment.

Air pollution

Other local emissions that are not possible to rule out is the wear particles from brakes and interaction between tire and road surface. These emissions are less studied than exhaust emissions. Braking particles are only emitted during braking and thus reduced mainly by reducing speed fluctuations. If braking is performed using electrical brakes the emissions of particles will be limited and the energy removed by braking can to some extent be saved in the battery of the vehicle to be used again later on.

Automated vehicles are able to keep the same (or different) transverse location at the road, thus wearing down the road surface more intensely in the wheel tacks. Thus, both wear, road maintenance and behaviour of the road dust will differ between NuMo and a traditional road.

Emissions from tire and road surface interactions depend on the choice of tire and on the specific road surface, together with effects from speed and acceleration/retardation. There is yet no detailed description of the quantitative effect from these variables, but there is some work done in the area. The wear particles often end up on the road to form a pool of dust that is later emitted as resuspension from the following vehicles. The pool of road dust can also increase by other sources, like deposits from construction dust or from heavy traffic carrying soil products. The resuspension process would be changed in this system as vehicle have smaller distances between them and move with a constant speed.

All emissions of wear particles are reduced if the speed is kept constant to a large degree, and thus this system with a focus on avoiding stopping during transport would be very beneficial to the emissions of wear particles.

[18] https://www.trafikverket.se/for-dig-i-branschen/Planera-och-utreda/Planerings--och-analysmetoder/Metod-for-samlad-effektbedomning/

Air pollution levels are heavily affected by weather, as higher wind speeds tend to decrease the concentrations by dilution and rain limits the resuspension of road dust. This imposes a large difference between systems including tunnels and systems with dedicated lanes on normal roads. For tunnels the concentrations of air pollutants can be much higher than in outdoor air, e.g. 100 times the outdoor air concentrations close to roads [14]. On the other hand, not many people are exposed to the air inside tunnels, and if this number is kept low the problem of tunnel air quality might be limited. The exiting of the vehicles inside the tunnel in that case might need a bit of thinking. Tunnel entrances, where tunnel air is emitted to the ambient, is also important to focus on according to air pollution emissions, but that does not differ from tunnels of today.

If the system is used in outdoor air the emissions are instead diluted and spread and thus affect also people at a larger distance from the traffic, and also noise from the traffic would spread to a larger area.

Noise

For electrical engines the engine is normally rather silent and most of the noise comes from the interaction between wheel and road surface. This sound is also limited in lower traffic speeds and there is an intensely discussed problem of electrical vehicles at low speeds that are so silent that they can be dangerous for pedestrians and bikers.

Noise and air pollutants spread more easily if the NuMo system is elevated, but there exist ways to limit this impact. For both noise and air quality the cost for the society is fully dependent on the exposure rate, as if there are no people affected the levels can be rather high of both air pollutants and noise with limited effects on economy.

Conclusion

The NuMo system gives possibilities to reduce changes of traffic speed, thus emissions of air pollutants as well as climate emissions are reduced in this system. Also wear particles will decrease due to reduced use of braking and changes in speed.

As the system will favor electrical vehicles the reduction of both air pollutants and noise will benefit from this introduction. If electrical roads are included in the system, the need of moving vehicles to refueling stations is also removed. With no drivers and no need to find fuel stations the need of stand-still will be limited.

Construction of dedicated lanes will, if only small cars are allowed on the lane, need less resources and emit less pollutants, including greenhouse gases. For tunnels that can be made smaller when excluding heavy vehicles, and for overpasses the economical as well as environmental gain will be large.

If NuMo is placed in tunnels the on-ground transport will decrease and the local environment around the traffic will improve both from a noise and air pollution perspective and from a societal perspective.

Challenges and further research

Development aspects

Communication

Both DSRC and 5G are under intensive investigation for C-ITS with close interaction between telecom and vehicle industries. NuMo needs to perform requirement analysis in terms of latency, range and reliability with consideration of available technologies and future traffic scenarios. This will have great impact on the control protocol design. In addition, Communication performance within tunnels need to consider the characteristics of tunnel, which should be an integral component for tunnel design and construction.

System control

NuMo system control involves both local control and global traffic system control. The local control involves the interaction protocol that enables e.g., cooperative intersection, platooning, access control and vehicle prioritization. Further development and testing of control mechanisms and interaction protocols with consideration of communication performance are needed. Standardization on C-ITS will need to be considered with extension of message sets and protocols to ensure interoperability. Global control needs to consider overall traffic flow within the NuMo system for potential congestion identification and to navigate vehicles to avoid links with high load or accidents.

Incident management

Incidents will be rare with electric vehicles and controlled admission to the network. Procedures for managing incidents are still necessary. Strategies for pulling and pushing vehicles, clearing of affected links, rescue vehicles and emergency evacuation need to be specified.

Modelling aspects

Simulations

Micro-simulation is a tool to evaluate traffic operation strategies. Several simulation models exist but need to be adapted for merge control, one-way tunnels, sloping ramps, off-line stations and a mix of private cars, vans and public vehicles.

Ride-sharing strategies

Shared rides reduce the number of vehicles and increase system capacity. Public taxi fleets should offer shared rides between dedicated stations. A multitude of ride-sharing strategies are possible, balancing efficiency against detours and delays. Special attention should be given to distribution trips out of transit hubs (train stations) and trips collecting passengers to mass transit departures. Transit hubs should be designed to allow cross-platform transfers to public taxis.

Empty vehicle management

Empty public taxis need to be directed towards waiting passengers and expected demand while at the same time minimizing vehicle mileage. Empty vehicles may also be given less priority in merges and in routing to avoid delays of other traffic.

Demonstration

Partners

A consortium needs to be created to enable a NuMo demonstration. The consortium needs to include a vehicle OEM, a communications partner and a city. An academic- or a research institute should plan the demonstration such that relevant knowledge can be generated.

Vehicle specifications

Vehicles need to have sensors and communication equipment and the intelligence to fuse and interpret information from many sources. Electric propulsion or other emission-free propulsion is a prerequisite for NuMo tunnel operation. NuMo offers an opportunity for OEMs to test and validate their technology in real operation in a semi-protected environment (SAE Level 4 autonomy).

Pilot sites

A pilot site for a NuMo network may include existing bus lanes and complementing connections at grade, elevated or in tunnels. The network needs to be fully connected, allowing transport between designated NuMo stations.

Evaluation

Important aspects of a demonstration will be to evaluate the impacts of NuMo on capacity, traffic flow, travel speed, travel mode choice, visual intrusion and public acceptance.

Business case

Mobility as a service is seen by most players in the industry as a strategic direction. The important message for everybody involved in mobility is that we, the public, demand seamless service in everything. Mobility, transport comes into that category and the companies such as Uber and Lyft have shown the way. When combined with Autonomous vehicles the business opportunities are huge, as are the downside challenges for traditional suppliers of mobility – the car manufacturers.

All major OEM are tackling this with substantial investments – Ford, GM, Daimler, Renault/Nissan – are but some who have announced investments or purchased operations with such a focus[19].

Business scenarios – who invests and who owns the infrastructure

The primary issue in the future of mobility is the role of infrastructure. Most current autonomous car hire / sharing relies on the use of existing infrastructure – the existing road network.

[19] https://en.wikipedia.org/wiki/Mobility_as_a_service

This separation of ownership and control poses fundamental questions about the relationship between the mobility vehicle and the supporting road infrastructure. Politically voters demand many things – often contradictory – such as more roads and parking and more trains and buses. The balance between those demands are also complicated by the frequent split of responsibility between central and local government.

Increasingly transport investment is also often financed separately with potential involvement of outside long-term investors.

The form of taxation which underpins these models will necessarily have to be revisited. Ideas such as road charging will probably be revisited in the knowledge of new forms of transport models.

We would like to examine a range of models in the next stage of our research.

OEMs' position in future mobility

There could be huge incentives for OEMs to invest in and even to control novel infrastructure. OEM that were early movers could establish a methodology of planning and construction which could be deployed on a global scale.

This team propose to examine in detail such models in forthcoming research.

Pricing strategies

The underlying pricing strategies will depend hugely on who controls investments. The interplay between politics, tax systems, protection of current models such employment possibilities in new systems will be reflected in pricing strategies. Currently it is striking that many new systems, such as Uber, rely on under-pricing in order to take dominant share in the market. This global competition is likely to continue with effects that deserve further examination.

Societal impacts

New demands on the road surface and structure

Autonomous vehicles will impose new demands on transport infrastructure as the vehicles will limit the meander to almost nothing. Thus, and as the NuMo system will only allow dedicated vehicles to the system, the roads can be built in a different way, i.e. more similar to tracks.

Following up on the construction phase of NuMo

As there are different ways of implementing the NuMo system, a study of the environmental and climate effects of the construction of different types of NuMo systems. The impact can be analyzed using klimatkalkyl, SEB and other tools mainly used by Trafikverket. In this way the impact from either an existing bus lane, a new tunnel, a now extra lane or a new overpass can be analyzed for sustainability and use of resources.

Political incentives

The political incentives to drive these developments are huge. All politics are local, but only those who are prepared with a vision stand any chance to create a better future. Politicians who look back to protect old patterns are likely to be swept away by those who have a positive idea of what the future should look like. This team want to help by outlining a viable future when it comes to mobility.

Social-technical aspects

The end user of NuMo will be normal travellers and human has to been considered as a central topic in the design and deployment of NuMo. It is thus important to investigate the social-technical issues such as the probability of persons unknown to each other would be ok with sharing a small compartment during transport; how the security for people entering and exiting the system inside the tunnels etc would be solved are important issues; would all different groups in the society be able to use the system or would some be excluded and what effect would this have to the urban environment?

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Appendix – Infrastructure Construction

General aspects related to construction

The construction of new urban systems must follow the general codes for constructing and for safety. This applies in particular for transport systems, which consist of autonomously operated vehicles. Even if the system allows a smarter design with smaller and lighter building components and cross sections, redundant measures need to be in place, which allow users of the systems to escape in case of an emergency in a safe way.

For the construction of a system as outlined in the previous chapters there are two main options:

- Underground systems
- Above ground systems

The former encompasses the existing or new ground level roads as well as elevated road systems. Ground level roads could be built with existing technology with addition of further installations such as communication lines/hubs, inductive charging stripes or charging stations and additional information and emergency systems. For elevated roads the size and load of the system should be adjusted to the actual needs: E.g. only one lane for each direction taking into account escape routes and exit stairs/emergency slides. Above ground systems have the advantage that in part existing road lines can be utilized for on or above ground constructions.

Underground systems are more challenging concerning realization and costs. Tunnels need to be constructed by trenching/cut and cover or without trenches. The latter construction technique is required, when the already existing building density does not allow trenching. However, the cut and cover technique can be useful for exit and entry points of the system Tunnel construction techniques for passing vehicles can be done by the drill and blast technique or by tunnel boring machines (TBM) of different sizes. This includes also micro tunneling techniques (microtunneling) for smaller diameters, which are bored with similar machines as large tunnels. Both construction types have their advantages and disadvantages. TBMs tunnel continuously, where the tunnel lining is applied directly after the bulk head of the machine. When applying TBMs the tunnel cross section needs to be round. The drill and blast technique leaves theoretically more options for cross section geometries, except that a vault shaped cross section is more suitable to withstand the pressure from the ground above.

In Europe, the general requirements concerning structural health and safety are essentially defined by the Eurocodes. The Eurocodes includes the basics for structural design, actions and traffic loads on constructions, design requirements for concrete, steel, wood, masonry, aluminum structures as well as underground constructions and constructions exposed to earthquakes. The Eurocodes, relevant for the new infrastructure system are listed below:

- Eurocode 0: Basis of structural design (EN 1990)

- Eurocode 1: Actions on structures (EN 1991, 4 parts)
- Eurocode 2: Design of concrete structures (EN 1992, 3 parts)
- Eurocode 3: Design of steel structures (EN 1993, 6 parts)
- Eurocode 4: Design of composite steel and concrete structures (EN 1994, 2 parts)
- Eurocode 5: Design of timber structures (EN 1995, 2 parts)
- Eurocode 7: Geotechnical design (EN 1997, 2 parts)
- Eurocode 8: Design of structures for earthquake resistance (EN 1998, 6 parts)

For instance, tunnels need to take into consideration Eurocode 0, 1,2 or 3 or 4, 7. Elevated roads and bridges are regulated by Eurocodes 0, 1, 2 or 3 or 4 or 5, 8 (if structure is in earthquake zone). The Eurocodes give general design rules, best practice and requirements in general and specifically for structures built in concrete, steel, timber, masonry and aluminum.

Additional to the Eurocodes, national requirements may apply in order to accommodate locally relevant structural aspects, e.g. locally restricted loading scenarios or local building practice. Road construction is regulated on a national level, usually formulated by the national road, traffic or transport administrations. The national rules are based on EN standards, national standards and special requirements for each country. For instance, in Sweden many requirements concerning materials and technical solutions are regulated in the AMA Anläggning document (Allmän material- och arbetsbeskrivning – Anläggning) [1]. In Germany the road administration defined specific requirements for planning, construction and maintenance of roads and road structures (tunnels, bridges) [2].

Road infrastructure systems are one of the most expensive built structures we have. They must be safe, durable, functional and flexible to accommodate future needs. The construction and maintenance of such systems consumes large amounts of money, which often derives partially or entirely from public funding. The amount of materials used for the construction project of an infrastructure system can be enormous and the daily load can be, depending on traffic density, deleterious to the system, requiring frequent and costly maintenance. This applies in particular to road pavements but also to structural materials used for tunnels and bridges.

Nowadays, it is not seldom that infrastructure constructions (e.g. bridges and tunnels) are planned for a service life between 120 and 150 years. Use, type and the way a construction was planned and built is defining service, maintenance and repair measures. Structural materials need therefore to be durable and reliable over long time periods, minimizing maintenance and repair cycles and maximizing the service life of a structure.

The choice of structural materials for the new infrastructures must therefore be based on the following factors:

- Durability
- Functionality
- Sustainability
- Availability
- Costs

In particular the cost factor together with durability and functionality rules often the choice of used materials. However, each of the factors influence themselves: E.g. Durability and availability influences sustainability and costs; functionality influences durability and sustainability. In the following some structural materials are listed with possible advantages and drawbacks.

Concrete: Is probably the most used material for transport infrastructures (roads, rail, airports). Concrete is a mix of a binder, sand and gravel. Nowadays, Portland cement-based binders are mostly used. In road pavements, bitumen as a binder for creating an asphalt concrete are dominant. For actual structures Portland cement-based steel reinforced concrete is often used and has the advantage that it is nearly everywhere available, it is durable to fairly low costs and it can be shaped in any form. It can be produced with a high variety in mechanical properties: Compressive strength from 10 MPa to 115 MPa are within the standardized range of strength values ([3]. Concrete can be prefabricated or mixed in a concrete mixing plant close to the construction site, transported and cast on-site. In Europe, most countries have a high density of concrete mixing plants so, that transport is usually covering only short distances. For longer distances, mobile mixing plants are usually used.

Drawbacks of the materials are the low tensile strength, which makes it necessary to reinforce it with steel rods or meshes. Also, to satisfy the structural requirements and the durability goals, ordinary reinforced concrete needs to be applied in fairly large amounts. This makes structures bulky and less slender. And this influences the sustainability of concrete, in particular CO_2 emissions, which are in the range of 100 to 300 kg per m^3 of concrete, depending on the type and amount of binder and the amount of reinforcement. Over time, this value is lowered due to the CO_2 uptake of concrete but nevertheless, concrete is yet not CO_2 neutral.

Steel: Is used mostly for bridge and sometimes underground constructions. It is a high strength material, can be formed to structural members with good load bearing capacity, both in tension and compression and can be welded, screwed or riveted to connect to other steel elements. If protected properly, it is a very durable material. The high strength of the material enables the architects and engineers to design fairly slender structures of sometimes high complexity (Figure 1).

Drawbacks are considerably high costs for steel as structural material and the need to prefabricate and transport steel elements to the construction site entailing higher transport costs. Also, the mechanical properties are less flexible since the strength values are within a fairly narrow range. Steel needs to be protected from corrosion and fire. The former requires anti-corrosion coatings in form of polymer paint and the latter intumescent coatings. Since the coatings' durability is not as long as the expected service life of a steel construction, they need to be reapplied in form of costly maintenance measures. Galvanization of steel could mitigate the corrosion problem to a certain degree but increases the costs for the steel and can cause safety/health problems when welded (galvanize poisoning). Steel produced mostly from scrap metal as a lower environmental impact compared to steel produced from pig iron. For pig iron production coke, a fossil derivate, is used as a reducing agent to transform the iron oxides/hydroxides into the metal form. In the process the coke is oxidized to CO_2, which is released into the atmosphere.

Figure 1 Example of a historical steel arch bridge construction, crossing the Rio Grande River close to Taos, New Mexico, U.S.A.

Wood: Wood as a structural material is gaining more prominence in countries with rich resources of it, e.g. Sweden. However, for transport infrastructures it is less applied due to its properties, when wider spans or high traffic loads are required. Wood is fairly easy to shape, is lightweight compared to steel and concrete and is a renewable resource with next to zero CO_2 emission balance.

Drawbacks for wood as a structural material are limitations concerning mechanical properties and the limited fire resistance, even when treated. This makes it hard to realize large structures with long spans within a reasonable cost frame. For instance, wood is usually applied for pedestrian bridges, overpasses or short vehicle traffic bridges. The durability of wood is limited to 30 to 50 years and in extremely exposed environments, as many structures for our transport infrastructure are situated, wood would need to be heavily treated to withstand such exposure conditions (e.g. underground, rain and salt spray) or frequent and costly maintenance cycles would need to be applied to keep the use of such structures safe. Wooden elements need to be pre-fabricated, transported and assembled on site.

Fiber reinforced polymer (FRP): FRP is a new group of structural materials, which have been applied more recently for bridge constructions. FRP is a composite material and consist of a reinforcement and an organic binder. The binder matrix is formed of epoxy, polyester or vinylester resins. As reinforcement fibers of glass, carbon or aramid are used [4]. The advantages of FRP are its lightweight character and good specific strength and stiffness properties. Those materials are nowadays widely used for repair and rehabilitation of structures and are more and more used as components in new structures (Figure 2).

FRP is a material with superior weight to performance values. However, it shows also a weakness towards shear forces, with only a weak shear strength. Furthermore, for the polymeric resin part there are no long-term data about its durability available. The track record for FRP is fairly short- and long-term data about the future performance are not yet available. The binder is based on polymers, which is mostly made from fossil derivates. Fire safety is therefore a weak point of the material and needs therefore extra protection, e.g. in form of coatings or fire retarding components in the resin. Sustainability is certainly an issue and the environmental impact of FRP, when used in large amount for infrastructure projects and in context to service life, needs still to be determined.

Figure 2 Vehicle bridge with FRP box girders (image source https://polskiprzemysl.com.pl/, left and https://www.muratorplus.pl/, right).

Other materials: Other structural materials, such as glass and aluminum, could be used as well but, if applied in larger amounts, would increase the costs for the system considerably and would entail a larger environmental impact.

In the end, a new infrastructure system needs to be safe and economic. This does not exclude solutions, which incorporate the application of different structural and non-structural materials. However, a designer of the system needs to balance between its size, expected service-life, sustainability towards environmental impact and maintenance and its costs. This is why for below and above ground systems concrete is often the choice as a structural material, because it is inexpensive, is readily available in most countries, has a good service life record and is sustainable over a long service life.

Below ground systems

Subterranean construction technologies

To move an autonomous traffic system underground is a convenient method to open-up space and avoid sound and visual impacts above ground. However, construction of underground systems can entail considerable costs, depending on the depth and the geological condition. The following methods are reviewed:

- Cut and Cover
- Bored tunnel method
- Shaft method
- Box jacking method

Cut and Cover

The Cut and Cover method is a system, which allows to build tunnels, which are fairly shallow. However, tunnels built with this method at 20 m and maximum 30 m were also constructed. The method allows excavation when the underground is loose (soil) or weakly bound underground (soft rocks).

The advantage of this method is its simplicity and it represents the most cost-effective method. The basic principle is to ram or drill side retaining walls into the ground, dig out the soil (Cut), install foundations, support walls, floors and a ceiling and cover the construction with soil again (Cover) (Figure 3). An advantage is the construction process does not need to completely interrupt an existing traffic flow, if the tunnel is, e.g. below an existing road. It can be constructed in sections, thus making construction sites only necessary at certain points along the planned excavation line [5]. The geometries of the tunnels can be executed quite flexible and can be rectangular, vaulted or rounded.

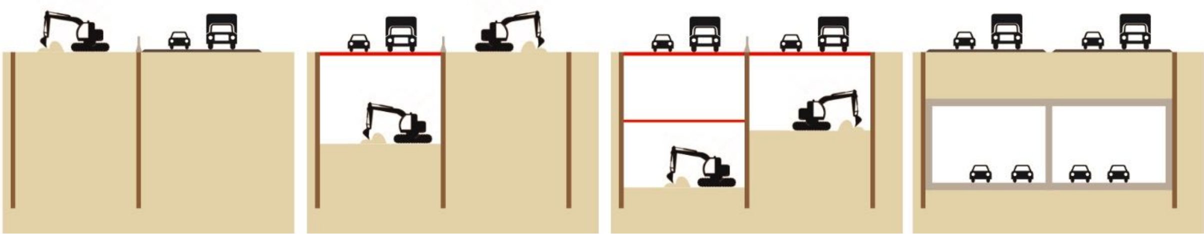

Figure 3 Principle of the Cut and Cover tunnel excavation method.

The Cut and Cover method is frequently used in urban environment. Particular care needs to be taken for ground water control and management. During excavation, water needs to be pumped out of the excavation trench. There is a risk that the lowering of the ground water level due to the pumping action leads to settlement and associated damages of nearby buildings, if no mitigating measures are taken. The collapse of the state archive in Cologne, Germany was caused by liquefaction of soil and the inflow of the soil suspension into a nearby Cut and Cover construction site with a defect retaining wall [6].

However, risks associated with Cut and Cover tunneling can be handled. The method is widely applied for railway and subway tunnels as well as for stations. There are several techniques, which are used under the Cut and Cover method and depend on the underground situation and the surrounding (e.g. number of buildings, number of roads, other underground structures, etc.) [7]. In urban areas the Cut and Cover method is a frequently applied method with examples in Gothenburg City (parts of the Västlänken railway tunnel), Madrid (subway) and New York (railway).

For the new transport system, the Cut and Cover excavation method might be in particular suitable for exit and entrance to the below ground transport system. These exit and entrance ways should be fairly close to the ground level to avoid steep inclines and long access side tunnels to the main tunnel(s).

Drill and Blast technique

The drill and blast technique can be applied if the underground is consisting of intermediate to hard bedrock, where the Cut and Cover method cannot be applied economically. The method is suitable for long to fairly short tunnels. The Drill and Blast method has low costs in investments but higher labor costs [8]. When applying the technique in densely populated areas, requirements have to be considered for protecting the urban environment from vibrations originating from blasts. Each country has usually own regulations for vibration control [9].

The method itself consists of drilling long blast holes into the solid rock, filling in the charges, compacting the charges, closing the holes and igniting the charges (Figure 4). The process is nowadays to a large extent automated. However, the method is not continuous. Before new holes can be drilled and charges set, the rubble from the blasts needs to be cleared away [8], which is usually done by conveyor belts or trucks. If the bedrock needs support, long rock support anchors are installed and sprayed over by shotcrete.

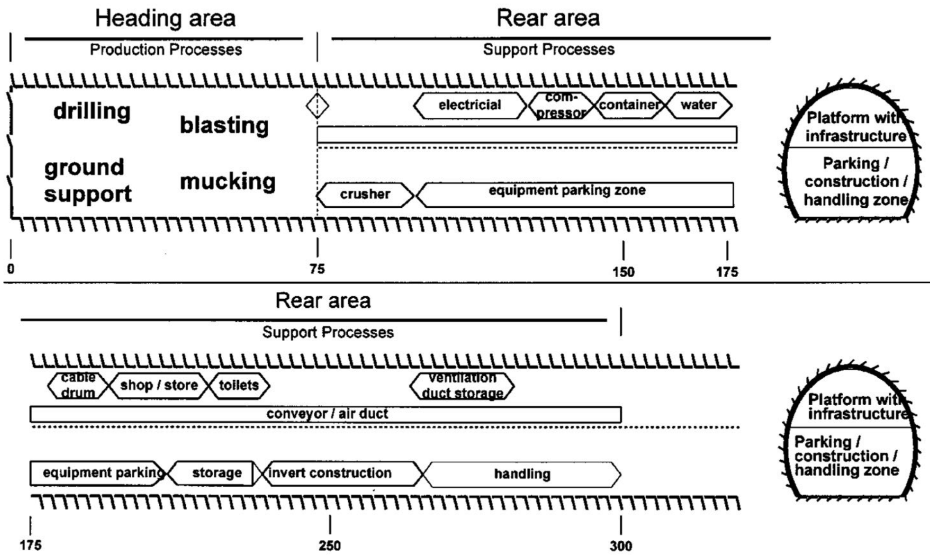

Figure 4 Drill and Blast functional areas with back-up system (from [8]).

The tunnel cross section can be flexible. Vaulted, rectangular or round geometries can be realized. After applying shotcrete as an initial support measure, concrete precast elements are usually applied if the bedrocks need a more permanent support.

Sweden and Norway have in many areas a solid bedrock, where the Drill and Blast technique was applied for many tunnels. Many of the subway tunnels in Stockholm were excavated by this technique.

Tunnel boring method

Tunnel boring is performed by tunnel boring machines (TBM). The method is highly mechanized and suitable for loose ground to hard rock (Figure 5). TBMs leave usually circular tunnel cross sections behind. Diameters range from 1.6 to 20 m. They are used for traffic tunnels and for pipe construction. The big advantage of TBMs is that the tunnel construction process is continuous and that behind the tunnel advance the tunnel lining can be permanently installed in form of concrete precast elements. A thrust system drives the entire machine into the rock, where a disk cutter removes the rock in the forward direction and where the rubble is removed by a conveyor belt system. The machine head is protected by hydraulic shields for stabilizing the surrounding rock [10].

Figure 5 A tunnel boring machine (TBM) in action. The system excavates and simultaneously applies the tunnel lining (from https://www.behance.net/gallery/20377183/ixtract-tunnel-boring-machine-TBM).

Depending on the underground geology, the excavated diameter and the ground water situation there exist several types of TBMs [10]:

- Hard-rock TBMs
    - Open-type, without any shields for stable bedrock with possibility for rock stabilization in form of grouted rock bolts and sprayed concrete lining
    - Shielded, for fractured hard bedrock with application of concrete precast elements as tunnel lining
    - Double-shielded, for fractured and stable hard bedrock with application of concrete precast elements as tunnel lining
- Soft-ground TBMs
    - Earth pressure balance (EBS) machines for soft ground with possibility to inject bentonite, polymers or foam into the soil ahead of the cutter head
    - Slurry shield (SS) for high ground water pressure and/or very loose ground consisting of sand/gravel
    - Open face type for stable soft ground with low water inflow

The disadvantages of the TBM method are high investment costs for the construction, transport and in-situ placement of a TBM (depending on the TBM diameter). However, for longer tunnels the economy and work environment (continuous construction process, nearly encapsulated work environment, fully automated construction process, considerable lower number of operational personnel) may outweigh the upfront costs for the TBM method [7].

For urban tunneling the use of the TBM method needs to be well planned in advance. This concerns in particular ground vibrations, existing tunnels, sewage and utility lines as well as deep foundations. Recent examples for the use of TBMs are for the subway systems in Barcelona, Spain and Karlsruhe, Germany as well as for the 57 km long Gotthard base tunnel in Switzerland.

For the new transport system, the TBM method is an ideal method for constructing underground tunnels in particular in urban areas, as long as the costs for a minimum tunnel system length is justifying the higher investment costs for a TBM.

Shaft method

The shaft method is used for shallow and deep tunnel locations and consist of vertical shafts for accessing the ground and lowering equipment onto the tunnel level. The horizontal tunnel is then constructed by the TBM or by the Drill and Blast method. For longer tunnels several shafts can be constructed along the tunnel line, which allows tunnel construction from multiple places at the same time. The shafts can be temporary, only existing during construction, or, as in many cases, can be utilized later for ventilation systems and/or escape routes.

Box jacking method

Box jacking is a method were a tunnel segment is placed into the ground by means of hydraulic jacks [7]. During jacking the box into the ground, ground material is excavated constantly. The segment is usually made of concrete and casted on-site next to the original placement (Figure 6). The box jacking method can be used for different tunnel geometries but is usually applied for fairly short segments.

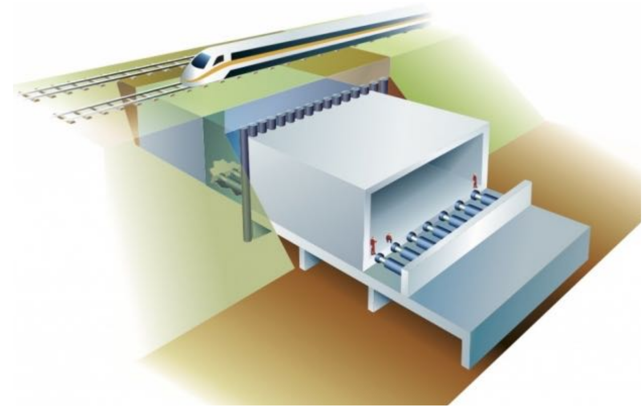

Figure 6 Principle of box jacking of a concrete tunnel segment into the ground (from: https://www.jackedstructures.com/box-jacking.html).

Excavation method

This method is applied in soft clayey underground or weak rocks. The excavation is done in cross-sectional segments and requires ground conditions, which are sufficient to support the excavation of these segments (Figure 7). After excavation the segments are directly supported by sprayed concrete. Usually the outer segments are excavated first, supported by temporary sprayed concrete linings. In a second step the inner section is excavated under deconstruction of the concrete linings of the first sections (Figure 7). After excavation, a water tight additional prefab or in-situ cast concrete lining is applied. In order to make the tunnel water tight, often a membrane between sprayed concrete and in-situ/prefab concrete is applied. The excavation method is compared to other methods, a fairly inexpensive construction process with low impact by vibrations. However, during excavation the existing ground water level needs to be lowered well below the tunnel sole, which in turn can create associated risks.

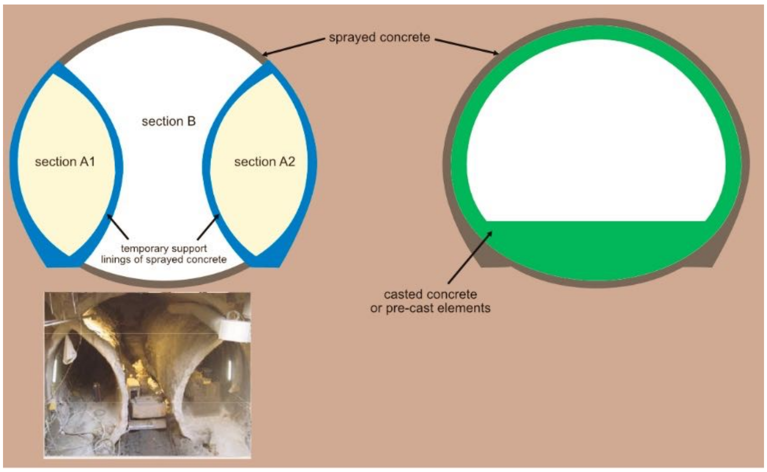

Figure 7 Schematics for the excavation method. First the sections A are excavated and then the section B. Under excavating section B the temporary support shotcrete linings are removed.

Design considerations

General

The cross-section geometry depends on the construction technique. Rectangular cross sections, vaulted or rounded geometries can be realized by the Cut and Cover, Box Jacking or Drill and Blast method. With the TBM method predominantly round cross sections are realized. All the previously discussed construction techniques can produce cross section sizes between 4 to 20 m.

The structural design of tunnels is based on the bedrock or soil conditions. In hard and stable bedrock structural support might be minimal and limited to drainage of water, application of rock anchors in combination with a sprayed concrete layer. Tunnels in loose ground (sand, gravel) or soil require a solid structural lining, nowadays mostly realized with pre-cast concrete elements.

The question, how to structurally dimension tunnels based on the surrounding ground situation was addressed by several rating systems. One of these, frequently applied for tunnels is the Rock Mass Qualification system (Q system). The Q-system was introduced in the 70s of the last century [11] and was further refined over the last decades [12]. The classification system is based on the quality of the ground calculated from many input parameters. The most important ground parameters for the Q-system are [11]:

- Relative block size
- Inter-block shear strength
- Active stresses

These parameters are subdivided into further, partially empirical, parameters:

- Relative block size
  - *Rock quality designation RQD* – degree of jointing
  - *Joint set number Jn*
- *Inter-block shear strength Jr/Ja*
- Active stresses
  - *Joint water reduction factor Jw*
  - *Stress calculation factor SRF* – Measures impact of fault zones or plastic swelling behavior of rocks/ground

The value Q is gained from the following equation [11]:

$$Q = RQD/Jn \cdot Jr/Ja \cdot Jw/SRF$$

An additional parameter was defined in form of the *Equivalent Dimension De* of the excavation, which is optioned by [11]:

De = Excavation span, diameter or height (m)/*Excavation Support Ratio ESR*

The value of the ESR is related to the intended use of the tunnel and contains also security aspects depending on the intended support system of the excavation. Values for ESR were given by [11] and are listed in Table 1.

Temporary mine openings	ESR = 3 – 5
Permanent mine openings, water tunnels for hydro power (excluding high pressure penstocks), pilot tunnels, drifts and headings for large excavations	1.6
Storage rooms, water treatment plants, minor road and railway tunnels, surge chambers, access tunnels	1.3
Power stations, major road and railway tunnels, civil defense chambers, portal intersections	1.0
Underground nuclear power stations, railway stations, sports and public facilities, factories	0.8

Table 1 Excavation Support Ratios (ESR) according to [11].

The equivalent dimension De plotted vs. the value Q is used for suggesting various support categories. The original chart by Barton et al. [11] was later updated by Grimstad and Barton [13] in order to incorporate steel fiber reinforced sprayed concrete, which became at this time the predominant method for sprayed rock support (Figure 8).

As Figure 8 shows, that the rock support system is mostly done in concrete in connection with grouting and securing unstable sections with rock bolts (Figure 9). In most cases, sprayed concrete is used; only for very to exceptional poor rock classes (Figure 8) a cast concrete lining is recommended, which is equivalent to soils or loose ground. The fields 1 to 9 indicate the thickness of the concrete support layer and the spacing of the rock bolts needed for securing the tunnel.

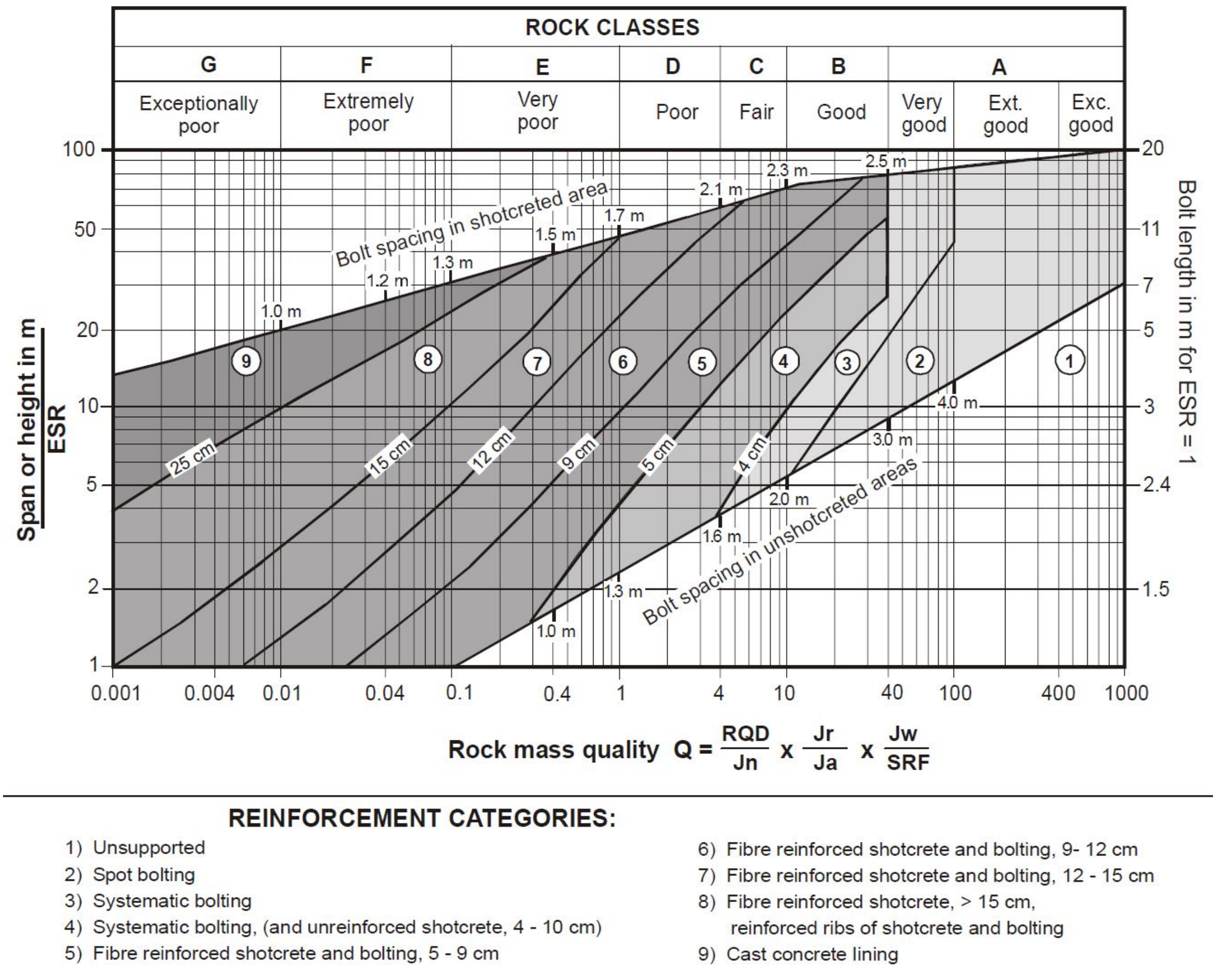

Figure 8 The Q support chart (from [14] after [13]).

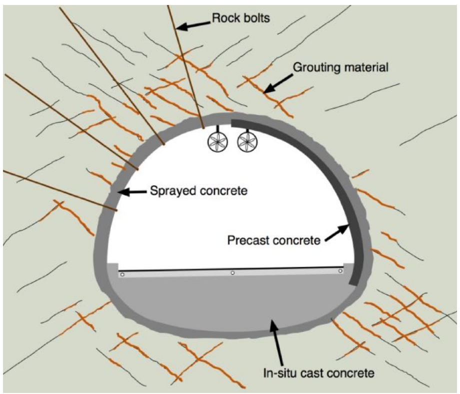

Figure 9 Example for a rock support system in tunnels based on steel rock bolts, grouting the surrounding fractured bedrock and linings of sprayed and/or casted/pre-cast concrete. Illustrations from [15].

The Q-system is seen as a useful system for the planning and implementation stage of tunnel construction and can be a valuable tool for ensuring all relevant information have been considered [14]. However, it will not replace detail procedure, which are related to stress levels of the bedrock, ground water exposure or project related features [14]. It was shown, that the Q-system works best in jointed rock masses, where instability is caused by rock falls. For other ground behavior in tunnels the Q-system is more limited in application. A evaluation of limitations for different ground systems can be found in Palmström & Broch [14].

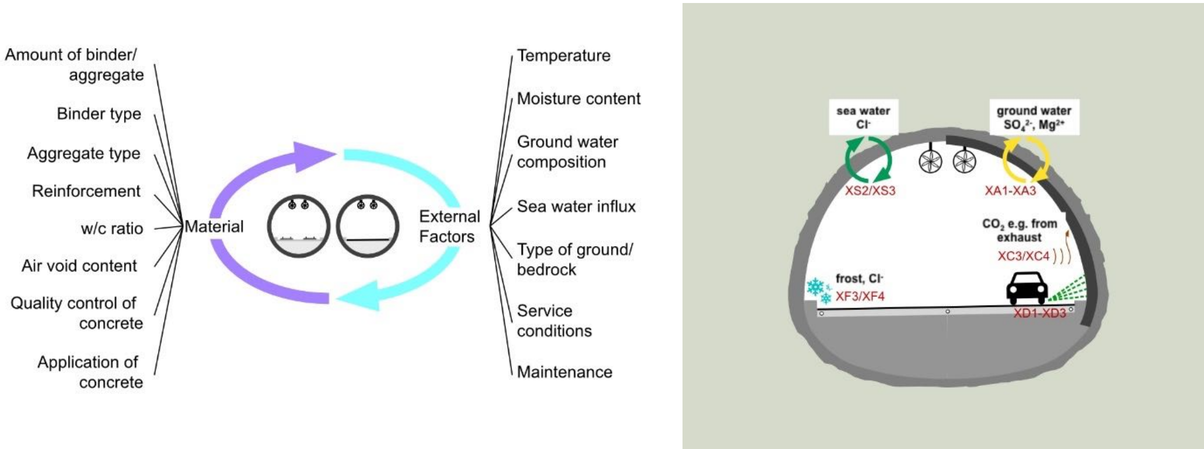

Figure 10 Influential factors for the performance and durability of concrete as a tunnel lining material (left illustration) and the exposure classes for concrete, which need to be considered in tunnel environments (right illustration). Both illustrations from [15].

Water management

Underground constructions need to be water tight. Depending on the ground situation there can be more or less water in the surrounding and/or periodically higher water levels present. In essence, there are two main water proofing concepts for underground structures such as tunnels.

The **drainage system** (Figure 11) is used when there is no hydraulic pressure on the structure and when the water table can be kept below the structure by the drainage system. The system usually consists of a water proofing membrane in the arch, which leads water to drainage pipes on the sides (Figure 11). The drainage pipes must be planned according to the amount of water expected for a tunnel in a specific location. The drainage pipes must be regularly maintained. This system is less costly concerning the water proofing system and allows tunneling under extreme conditions. However, drainage pipes need to be cleaned regularly and might, depending on the ground water composition, have a tendency to block due to sintering of the pipes [16].

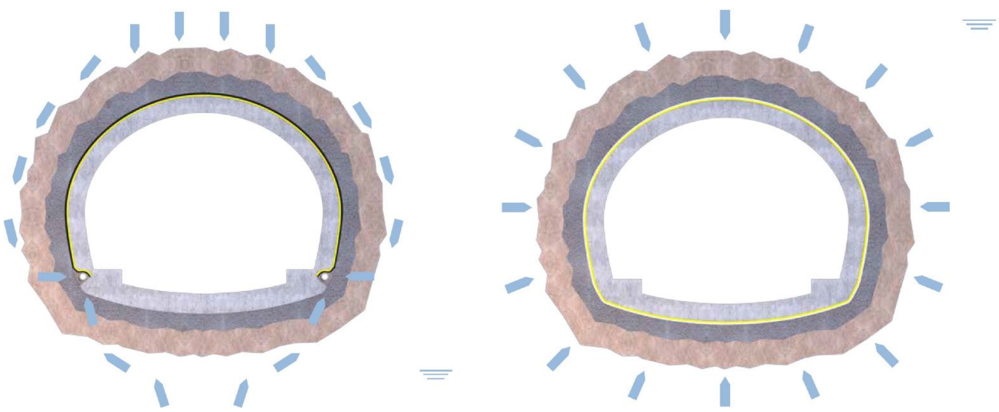

Figure 11 Two water proofing concepts (from [16]).

The **barrier system** (Figure 11) is used when there is a permanent hydraulic pressure on the tunnel. The barrier system has a waterproofing lining which protects the entire structure from water ingress and chemical attack. The barrier system requires no maintenance and can be equipped with an in-built control and injection system for redundancy. This system is, however, increasing the overall construction costs [16].

The waterproofing lining for both systems consists usually of polymer sheet membranes or sprayed polymer membranes (e.g. PU/PUR). In some cases, waterproofing membranes are combined with water tight concrete. The concrete is specifically customized to have a reduced crack tendency with minimum crack width and is usually of higher quality.

Material considerations

Tunnel construction is heavily relying on concrete as a main construction material. This is due to its easy applicability for initial ground support in form of sprayed concrete, its good mechanical properties and its fairly inexpensive costs. For sprayed concrete, steel fibers are nowadays used as the main reinforcement material. In-situ cast concrete is mostly applied to the tunnel sole and for vertical shaft structures. With tunnel construction with the TBM method, pre-cast concrete segments are directly placed as tunnel lining. If needed, the gap between tunnel lining and bedrock can be grouted for better flow of stresses around the tunnel. The factors influencing the durability and performance of concrete in tunnel environments are shown in Figure 10. Next to the mechanical and stability factors of the excavation and the tunnel structure, the one shown in the Figure influence mostly the durability of the concrete as a material. For concrete tunnel applications, the exposure classes according to EN 206 [3] are applying for tunnels as illustrated in Figure 10 (right) [15].

Though concrete is often not seen as the most sustainable material, in the tunnel environment it is the most durable with the best performance results. At the moment there are no alternatives to concrete, which give the same performance values and durability in the same cost range. Concrete as a material has a long service record for tunnel applications. Nowadays, service life requirements for tunnels with concrete linings are often above 100 years with a minimum of maintenance interventions. On these long life-span tunnels, sustainability increases if the maintenance measures can be kept to a minimum.

Steel as a structural material would have to be heavily protected against corrosion; other steel types as the standard construction steel, such as galvanized or stainless steel, would be too costly and too unsustainable to be used for larger/longer tunnels. The gap between steel segments and the bedrock would need to be grouted with a cement mortar in order to allow an optimal stress flow around the tunnel.

Other material solutions such as wood, would perform mechanically not sufficiently and the durability would be too short lived. Fiber reinforced polymers would need to be used in such amounts that the tunnel would be too costly and unsustainable. Also, the track record of fiber reinforced polymer composites is too short to have reliable data for a long-term performance prediction.

Another material approach is the use of ultra-high performance concrete (UHPC) with fiber or textile reinforcement [17]. The material itself has higher costs compared to ordinary concrete but due to its mechanical behavior and durability it can help to save 30 to 50 % of the total amount of material used, e.g. for precast tunnel segments. However, similar to FRP UHPC does not show not the same track record of performance compared to standard concrete and an introduction of the fairly new material into tunnel construction will take some time in order to overcome the tough regulatory processes within the construction area.

Safety requirements for tunnels

Tunnels are confined spaces with limited exit routes in case of emergencies. Experience from the past showed a lower risk from tunnel collapses due to the mechanical loading compared to fire events. Devastating fires with many casualties, e.g. in the Mont Blanc tunnel in 1999 or the Kaprun tunnel in 2000, showed the consequences of missing safety precautions and changed the way how tunnels are constructed nowadays. After these fires, which happened within the European Union, the European Commission started an initiative towards increasing fire safety in tunnels, which were formulated into the Directive 2004/54/EC of the European Parliament [18].

The Directive 2004/54/EC [18] takes the following parameters into account:

- tunnel length
- number of tubes
- number of lanes
- cross-sectional geometry
- vertical and horizontal alignment
- type of construction
- uni-directional or bi-directional traffic
- traffic volume per tube (including its time distribution)
- risk of congestion (daily or seasonal)
- access time for the emergency services
- presence and percentage of heavy goods vehicles
- presence, percentage and type of dangerous goods traffic
- characteristics of the access roads
- lane width
- speed considerations
- geographical and meteorological environment

The minimum safety requirements of this document address the following topics:

Traffic volumes: Annual average daily traffic through a tunnel per lane. It takes also into account the type of vehicles (cars, trucks, …) and time dependent peak times.

Number of tubes and lanes: If the expected number of vehicles for a 15 years forecast exceeds 10 000 vehicles per day and lane a twin-tube tunnel with unidirectional traffic is required.

Tunnel geometry: Special safety considerations for cross sectional design and its horizontal and vertical alignment of a tunnel and its access roads. No longitudinal gradients above 5 % permitted for new tunnels (unless no other solution is possible) and gradients higher than 3 % need special reinforcement measures (based on risk analysis). For lane width for heavy vehicles less than 3.5 m additional measures need to be taken (based on risk analysis).

Escape routes: New tunnels without emergency lanes an emergency walkway (elevated or not) needs to be installed. Exceptions: If tunnel design details do not allow this or if implementation would cause disproportional costs **and** the tunnel is unidirectional and is equipped with a permanent surveillance and lane closure system. In existing tunnels without emergency lane/walkway, additional measures need to be installed to ensure safety.

Emergency exits: For allowing users to leave a tunnel without their vehicles in case of accident and/or fire. Can consist of:

- Direct exits from tunnel to outside
- Cross connections between tunnel tubes
- Exits to an emergency gallery
- Shelter with escape route separate from the tunnel tube

Emergency exits needs to be provided if analysis of relevant risks (e.g. how far and

quickly smoke travels under local conditions) indicate that ventilation and other safety provisions are insufficient to ensure the safety of road users. New tunnels need to provide emergency exits if the traffic volume is higher than 2 000 vehicles per lane. In existing tunnels longer than 1 000 m and a traffic volume higher than 2 000 vehicles per lane an evaluation of the implementation of an emergency system needs to be performed. The distance for emergency exists needs to be below or equal to 500 m. Doors or other barriers needs to be implemented for emergency exists to prevent smoke and heat transport beyond the affected tunnel tube.

Access for emergency services: Tunnels must be dimensioned to allow emergency services access to the accident/fire site. In twin tube tunnels cross connections need to be installed every 1 500 m.

Turnouts: Need to be installed every 1 000 m for new bidirectional tunnels longer than 1 500 m and a traffic volume of more than 2 000 vehicles per lane, if emergency lanes are not provided. Turnouts need to include an emergency station.

Drainage: If transport of dangerous goods is permitted the drainage systems must allow the flow-off of toxic and flammable liquids by slot gutters or other measures. The drainage system should be designed to prevent fire and flammable liquids from spreading inside the tubes and between the tubes.

Fire resistance: For all tunnels sufficient fire resistance of the materials and construction parts needs to be ensured.

Lighting: Normal lighting needs to be provided for save operation. Additionally, safety lightning must be installed in case of a power outage. Evacuation lighting in form of illuminated markers need to guide users safely to emergency exits. Markers should not be higher than 1.5 m above ground.

Ventilation: Ventilation systems are mainly for:

- the control of pollutants emitted by road vehicles, under normal and peak traffic flow
- the control of pollutants emitted by road vehicles where traffic is stopped due to an incident or an accident

- the control of heat and smoke in the event of a fire

Required are mechanical ventilation systems for tunnels longer than 1 000 m with a traffic volume of more than 2 000 vehicles per lane. In tunnels with bi-directional and/or congested unidirectional traffic, longitudinal ventilation "… shall be allowed only if a risk analysis … shows it is acceptable and/or specific measures are taken, such as appropriate traffic management, shorter emergency exit distances, smoke exhausts at intervals." [18]. Transvers/semi transvers ventilation is required in tunnels where a mechanical ventilation is necessary, and a longitudinal ventilation is not allowed. Tunnels with bidirectional traffic and a traffic volume higher than 2 000 vehicles per lane, longer than 3 000 m and with a control center and transvers/semi transvers ventilation it is required to:

- Install air and smoke extraction dampers
- Monitor air velocity and steering processes of the ventilation system and adjusted accordingly

Further requirements concern the prerequisites for the following items:

- Emergency stations
- Water supply
- Road signs
- Control center
- Monitoring system
- Tunnel closing equipment
- Communication systems
- Power supply and electrical circuits
- Fire resistance of equipment

Table 2 summarizes the minimum requirements for safety measures in tunnels.

In parallel, many European countries updated their requirements for tunnel constructions, also concerning required safety measures. In Sweden, this is described in the document TRVK Tunnel [19]. The documents are taking national legislation into account and define requirements towards safety, risk assessment, environmental impact and management and quality control routines.

● mandatory for all tunnels ❍ not mandatory
* mandatory with exceptions ◐ recommended

SUMMARY OF MINIMUM REQUIREMENTS			Traffic ≤ 2 000 veh. per lane		Traffic > 2 000 vehicles per lane			Additional conditions for implementation to be mandatory, or comments
			500-1 000 m	>1 000 m	500-1 000 m	1 000-3 000 m	>3 000 m	
Structural Measures	2 tubes or more	§2.1						Mandatory where a 15-year forecast shows that traffic > 10 000 veh./lane.
	Gradients ≤ 5 %	§2.2	*	*	*	*	*	Mandatory unless not geographically possible.
	Emergency walkways	§2.3.1 §2.3.2	*	*	*	*	*	Mandatory where there is no emergency lane, unless the condition in §2.3.1 is respected. In existing tunnels where there is neither an emergency lane, nor an emergency walkway additional / reinforced measures shall be taken.
	Emergency exits at least every 500 m	§2.3.3 - §2.3.9	❍	❍	*	*	*	Implementation of emergency exits in existing tunnels to be evaluated case-by-case.
	Cross-connections for emergency services at least every 1 500 m	§2.4.1	❍	❍ / ●	❍	❍ / ●	●	Mandatory in twin-tube tunnels longer than 1 500 m.
	Crossing of the central reserve outside each portal	§2.4.2	●	●	●	●	●	Mandatory outside twin- or multi-tube tunnels wherever geographically possible.
	Lay-bys at least every 1 000 m	§2.5	❍	❍	❍	❍ / ●	❍ / ●	Mandatory in new bi-directional tunnels >1 500 m without emergency lanes. In existing bi-directional tunnels >1 500 m: depending on analysis. For both new and existing tunnels, depending on extra usable tunnel width.
	Drainage for flammable and toxic liquids	§2.6	*	*	*	*	*	Mandatory where transport of dangerous goods is allowed.
	Fire resistance of structures	§2.7	●	●	●	●	●	Mandatory where a local collapse can have catastrophic consequences.
Lighting	Normal lighting	§2.8.1	●	●	●	●	●	
	Safety lighting	§2.8.2	●	●	●	●	●	
	Evacuation lighting	§2.8.3	●	●	●	●	●	
Ventilation	Mechanical ventilation	§2.9	❍	❍	❍	●	●	
	Special provisions for (semi-) transverse ventilation	§2.9.5	❍	❍	❍	❍	●	Mandatory in bi-directional tunnels where there is a control centre.
Emergency stations	At least every 150 m	§2.10	*	*	*	*	*	Equipped with telephone and 2 extinguishers. A maximum interval of 250 m is allowed in existing tunnels.
Water supply	At least every 250 m	§2.11	●	●	●	●	●	If not available, mandatory to provide sufficient water otherwise.
Road signs		§2.12	●	●	●	●	●	For all safety facilities provided for tunnel users (see Annex III).
Control centre		§2.13	❍	❍	❍	❍	●	Surveillance of several tunnels may be centralised into a single control centre.
Monitoring systems	Video	§2.14	❍	❍	❍	❍	●	Mandatory where there is a control centre.
	Automatic incident detection and/or fire detection	§2.14	●	●	●	●	●	At least one of the two systems is mandatory in tunnels with a control centre.
Equipment to close the tunnel	Traffic signals before the entrances	§2.15.1	❍	●	❍	●	●	
	Traffic signals inside the tunnel at least every 1 000 m	§2.15.2	❍	❍	❍	❍	◐	Recommended if there is a control centre and the length exceeds 3 000 m.
Communication systems	Radio re-broadcasting for emergency services	§2.16.1	❍	❍	❍	●	●	
	Emergency radio messages for tunnel users	§2.16.2	●	●	●	●	●	Mandatory where radio is re-broadcasted for tunnel users and where there is a control centre
	Loudspeakers in shelters and exits	§2.16.3	●	●	●	●	●	Mandatory where evacuating users must wait before they can reach the outside.
Emergency power supply		§2.17	●	●	●	●	●	To ensure the functioning of indispensable safety equipment at least at during evacuation of tunnel users.
Fire resistance of equipment		§2.18	●	●	●	●	●	Shall aim to maintain the necessary safety functions.

Table 2 Summary of minim requirements from [18].

Above ground systems

Types of elevated structures - Bridges

To move an autonomous traffic system above ground is maybe a convenient method to open-up space from the existing ground level road system. Disadvantages of above ground systems are sound (maybe surmounted by electrical autonomous cars) and visual impacts. Construction of above ground systems can entail considerable costs, depending on the type of above construction system and also the geotechnical characteristics of the foundation. Elevated traffic systems can be constructed with existing bridge building technologies. The following types of bridges are reviewed [20]:

- Beam
- Arch
- Suspension
- Cable stayed

Regarding the construction technology 2 methods are reviewed:

- Precast segmental construction
- Incremental launching method

Regarding the material used in bridges can be classified as:

- Reinforced and/or prestressed concrete
- Steel Bridges
- Wood bridges

Bridges are structures with the purpose of getting from one side of natural obstacles such as rivers, valleys, etc or artificial obstacles such as roads and railways to the other side. Mainly bridges has 2 parts the supports and the deck, the distance between the supports is called span.

Beam or girder bridges

They are mainly constituted by horizontal elements or beams that are supported on 2 or more elements called piers. On top of the girder is the deck with walkways and/or the road lanes [20]. The resisting concept on the beam bridge is related to the height of the beam and the moment of inertia of its cross-section. This type of bridge is the most common type of bridge. This type of bridge is easy to build, normally prefabricated beams are used and is quite cost efficient. Usually concrete and steel girders are used. However, fiber reinforced polymer (FRP) is now used as an experimental material for girder production (Figure 2). Different types of girders are usually used: Rolled steel girders (usually I-beam or wide flange beam), Plate girders (steel plates are connected together to form the cross-sectional shape) and box girders (shaped as a box with sides, top and bottom).

The span length of the girders depends on the girder cross section shape/size and type of materials used. In practice, effective spans between 25 and 150 m are used but the longest effective span for a girder bridge is 300 m (Costa e Silva bridge in Brazil). The girder approach is often used also for specific sections of an elevated road or bridge system were sections on land are realized with a girder construction and bridging a larger span over a river or valley with another type of bridge construction (Figure 12).

Figure 12 The Köhlbrand bridge in Hamburg, Germany. The main bridge part with the pylons is a cable-stayed bridge, but the access parts are box girder bridges.

Arch bridges

Arch bridges represent probably one of oldest bridge construction methods (Figure 13). The main element of an arch bridge is, as the name suggests, a load bearing arch which is under compressional loads. The horizontal forces, which effect the arch when loaded are counteracted by abutments on each side of the arch. This allows to carry higher loads compared to beam bridges of similar spans [21].

Arch bridges can be built from all kinds of materials, which have good compressional and shear properties. In the past, stone and brick were the main materials used for arch constructions. However, during industrialization steel was more and more used (Figure 1) and in modern times concrete is next to steel the main material for arch bridges (Figure 13).

Typically, arch bridges are built with multiple arches, when stone or bricks were used, usually with a shorter span length for each arch. With steel or concrete as main materials single arch bridges of wider span could be realized as well. The span of the longest single arch bridge, the Chaotianmen Bridge in China, is 552 m but spans are generally shorter in the range of 50 to 400 m. Arch bridges are fairly simple to realize and even pre-fabricated elements of steel and concrete can be used. One of the first vehicle bridges from ultra-high performance concrete (UHPC) was constructed with prefab elements [22]. The bridge has a span length of 157 m and inside the single hollow UHPC elements post tension cables support to counteract the horizontal forces and lead them to the abutments. In this case the abutments could be made fairly small.

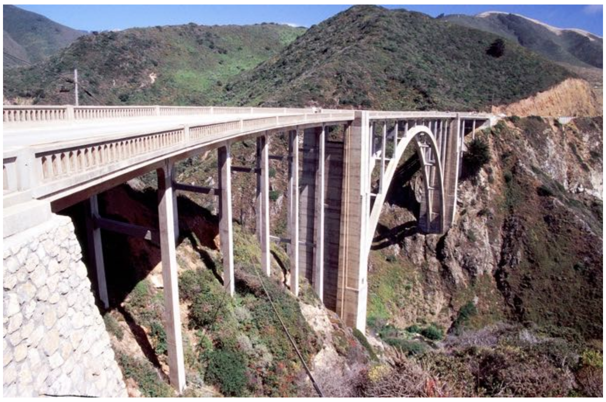

Figure 13 Roman arch bridge in Cordoba, Spain (upper left). The Bixby Creek Bridge in California, USA, is an example of a more modern open spandrel arch bridge made with reinforced concrete (upper right). The Wild Bridge in Austria, constructed from ultra-high performance concrete (left, image taken from https://www.wild.at/unternehmen/evolution/).

Suspension bridges

In suspension bridges the main load of a deck is carried by suspension cables, which are spanned between two towers on each end of the bridge. To support the towers, the cables usually run further into cable foundations. The load of the deck is transferred by vertical suspenders to the main suspension cables. The main force in this type of bridges are in tension: Between the main cables and between the suspender cables, which hold the bridge deck(s) [20]. The towers transfer the tension loads vertically into the tower foundations (Figure 14). Rope bridges, to cross deep valleys or gorges in mountainous areas, are based on the suspension principle.

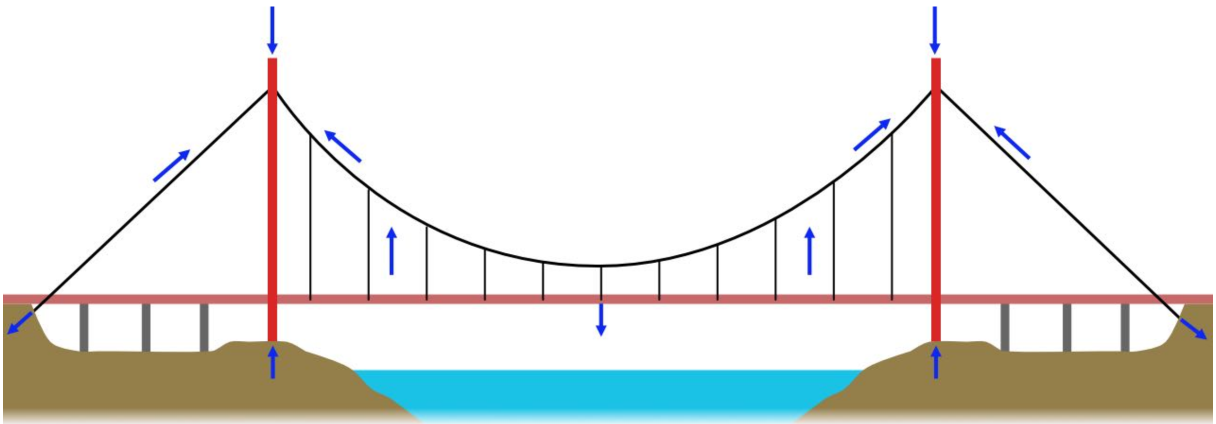

Figure 14 Principle of a suspension bridge. The arrows indicate the flow of forces.

Nowadays, suspension cables consist of steel wire strands but older types consisted of chain links or linked bars. Steel wire cables are considered safer since the multiple strands of steel wires not only add strength but increases redundancy (a few faulty strands in a steel wire cable will not fail the entire steel cable). The older chain or linked bar suspension bridges bear a higher risk of failure due to the fewer elements, which transfer the load of the bridge deck to the towers.

Suspension bridges are generally slender since the load bearing elements consist of mainly steel components (Figure 15). Only the towers and the bridge deck are sometimes made from reinforced concrete. The slenderness makes suspension bridges, however, more sensitive to strong shear winds. In this case special profiling of stiffness and aerodynamic may be required to avoid excessive vibration of the bridge deck [23]. With the suspension system the bridge deck is usually not as stiff as with other constructions. Heavy, localized loads, e.g. heavy trains, may cause distortions of the deck.

Figure 15 The Älvborgsbron over the mouth of the Göta älv river is a suspension bridge with steel wire cables from the 60s.

The bridge deck itself consists usually of an open truss structure. Plate girder constructions proofed to be aerodynamically not stable in the past; in some cases they contributed to the collapse of bridges (e.g. Tacoma Narrows Bridge in 1940). However, developments in bridge aerodynamics allowed to reintroduce very shallow box girders in the 1960s.

Suspension bridges provide the longest span lengths. The longest suspension bridges have a span length in the range between 1500 to 2000 m. At the moment, the longest bridge with a suspension design is the Akashi Kaikyo Bridge in Japan with a main span of 1 991 m.

Cable-stayed

Cable stayed bridges have usually one or more pylons (towers) from where cables support the bridge deck. The cables run diagonal from the pylons in a fan like pattern to the bridge deck. The load of the bridge deck is transferred via the cables and the pylons by downward compression into the pylon foundations [20]. The main cables are free to move on bearings in the pylons. With this construction type the pylons are the main load bearing structures. They are made from steel or reinforced concrete. The span of a bridge is defined by the number and the height of the pylons.

There are different types of cable-stayed bridges (Figure 16). The mono design uses a single cable and is not used frequently. One infamous example is the Ponte Morandi in Genova, Italy, which partially collapsed in August 2018. More common designs are the harp design, with a nearly parallel cable arrangement and the fan design with a central point of the cables in the top of the pylons. The star design is less common with cables arranged in different heights in the pylons but closely concentrated holding the bridge deck.

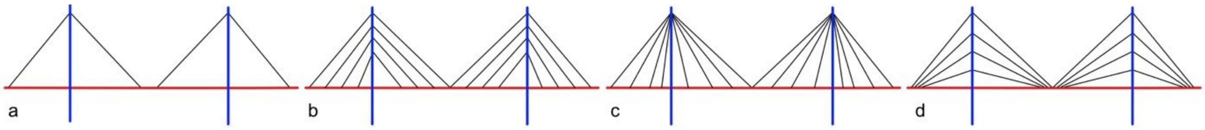

Figure 16 Different types of cable-stayed bridges. a. Mono design, b. harp design, c. fan design, d. star design.

The pylon arrangement and geometries can be different. They can be for two cable levels (one each side of the bridge deck) or only one (in the middle of the bridge deck). Each of the two types have several sub-types with different designs of the pylons and cables. The bridge deck is often constructed in concrete as well as in steel or steel-concrete composite. Concrete bridge decks consist of prestressed aerodynamically designed flat box girders and steel similarly designed prefabricated boxes of steel plates combined to an orthotropic deck.

Cable-stayed bridges are very common in more recent bridge designs. In the past, longer bridge spans were mostly realized with suspension bridges but better materials and better design possibilities (e.g. numerical modelling) of the structure and aerodynamics led since the last 30 years to longer spans, like the Russky Bridge in Russia with a span of 1 104 m. The Öresund Bridge between Denmark and Sweden is the longest cable-stayed bridge with two decks, one for traffic, the other for railway (Figure 17).

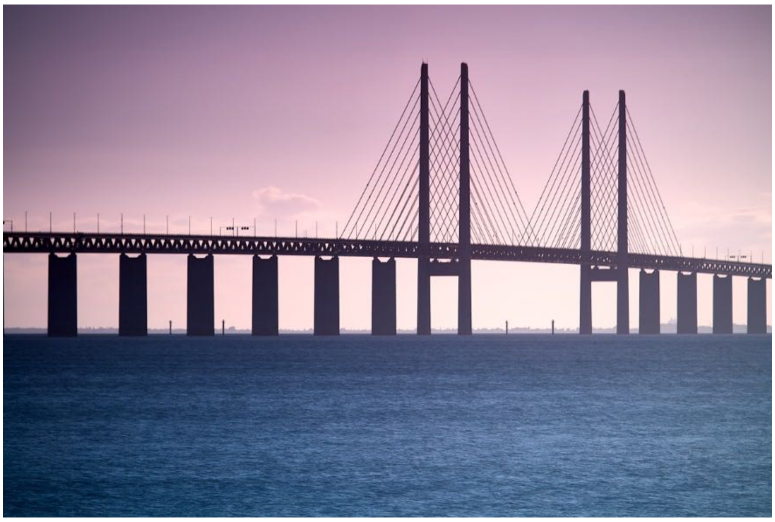

Figure 17 Öresund Bridge between Denmark and Sweden. The central part of the bridge is a cable-stayed bridge in the harp design.

Construction technologies

Precast segmental construction

Precast segmental bridge constructions use pre-fabricated elements, which are transported to the construction site and put together. Pre-cast elements of concrete consist mostly of box girder segments which, starting from the superstructure on top of the first pier, are segmentally mounted to the next pier (Figure 18). The elements are hoisted with a gantry and set in place [24]. The connection between each box segment is done by steel couplings. Post-tension cables are installed and stressed after installing a number of segments. Cable canals and ends are grouted with cement injections [25].

Figure 18 Precast segmental construction in practice. Images from www.asbi-assoc.org.

Precast sequential construction is cost effective and fast. Bridge segments can be pre-fabricated in large numbers at a concrete precast plant and used when needed. Precast segmental constructions can be done with different types of bridges but is usually done with box girder bridge decks. The single concrete elements have usually a length between 3 and 4 m.

Incremental launching method

With the incremental launching method as shown in Figure 19 and Figure 20, the actual construction of the bridge superstructure is done in a casting bed behind the bridge abutment. Each segment is, when casting and curing is done, jacked exactly the length of the first segment towards the piers. The process is repeated until the bridge is in its final position. Each pier has launching bearings and the first segment a launching nose [20]. The elements are with pre-stressed tension cables with each other connected, which increases the overall stiffness of the superstructure [26]. The bearings on the piers consist usually of PTFE (Teflon) coated plates.

This method can also be applied to pre-fabricated steel segments. The fabrication is done not on the bridge construction site but at a factory. The steel segments are then similarly jacked into place. A launching nose, due to the reduced deadloads for steel segments, is usually not necessary.

Even though the method is not the most economic method in all cases of bridge construction, it comes with significant advantages [26]:

- Minimal environmental disturbance
- Smaller but more concentrated area for superstructure assembly required
- Better working conditions since all actual construction work is done on ground

The method can be used for a wide range of challenging topographies with limited or restricted access [26]:

- Deep valleys

- Deep water crossings
- Steep slopes or poor soil conditions
- Protected areas below the bridge

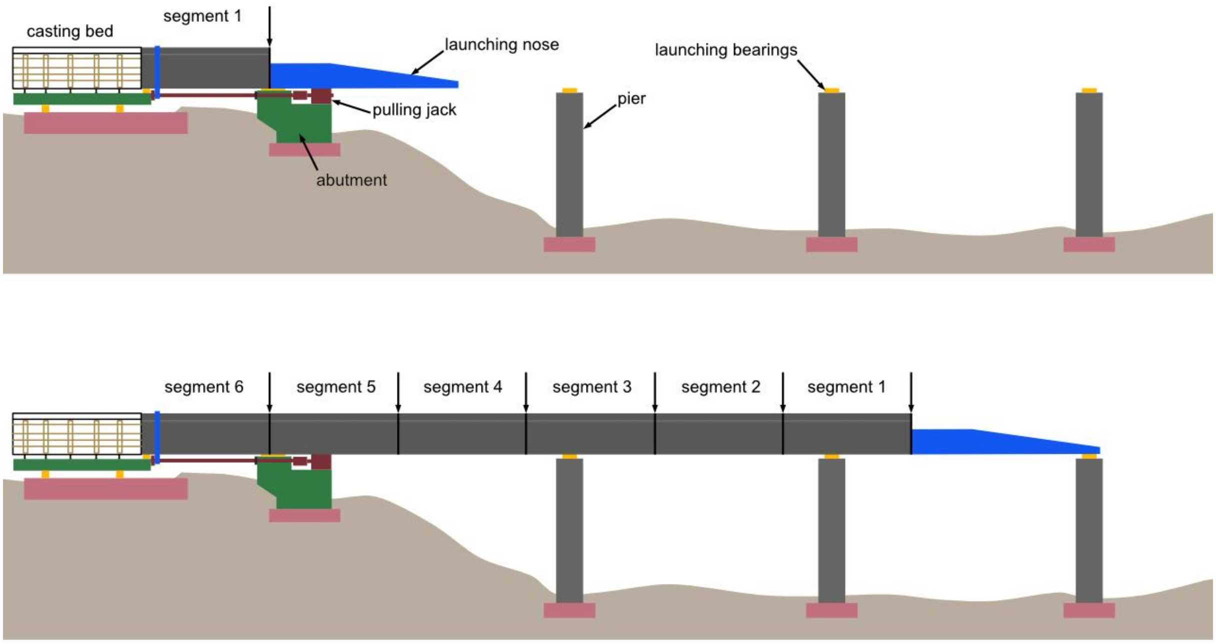

Figure 19 Principle of the incremental launching method.

Figure 20 Example for a bridge construction with the incremental launch method (from http://www.amsteele.com).

Design considerations

General

The structural design of road bridges is a complex task which includes many aspects of structural parameters (self-loads, geotechnical loads), environmental loads (weather exposure, earthquakes, wind and snow loads) as well as loads caused by the traffic on the bridge. The main regulatory documents are the Eurocodes mentioned above. Figure 21 and Table 3 illustrate the type of Eurocodes and additional standards to be used for elevated traffic structures.

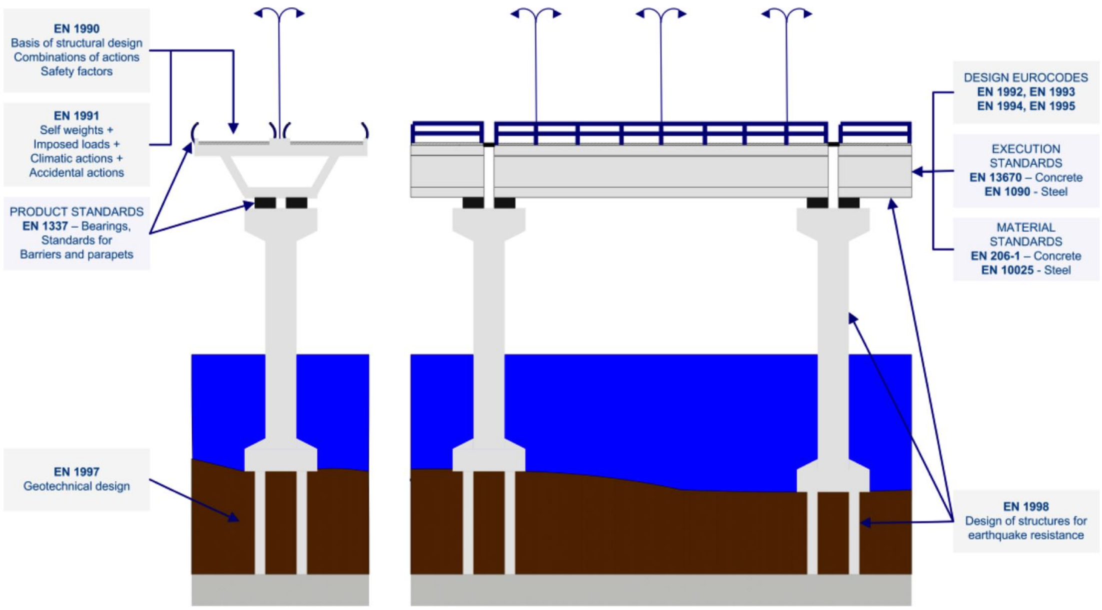

Figure 21 Summary of standards to be used for steel and concrete bridge constructions (from [27]).

EN Part	Scope	Concrete	Steel	Composite
EN 1990	Basis of design	√	√	√
EN 1990/A1	Bridges	√	√	√
EN 1991-1-1	Self-weight	√	√	√
EN 1991-1-3	Snow loads	√	√	√
EN 1991-1-4	Wind actions	√	√	√
EN 1991-1-5	Thermal actions	√	√	√
EN 1991-1-6	Actions during execution	√	√	√
EN 1991-1-7	Accidental actions	√	√	√
EN 1991-2	Traffic loads	√	√	√
EN 1992-1-1	General rules	√		√
EN 1992-2	Bridges	√		√
EN 1993-1-1	General rules		√	√
EN 1993-1-5	Plated elements		√	√
EN 1993-1-7	Out-of-plane loading		√	√
EN 1993-1-8	Joints		√	√
EN 1993-1-9	Fatigue		√	√
EN 1993-1-10	Material toughness		√	√
EN 1993-1-11	Tension components		√	√
EN 1993-1-12	Transversely loaded plated structures		√	√
EN 1993-2	Bridges		√	√
EN 1993-5	Piling		√	√
EN 1994-1-1	General rules			√
EN 1994-2	Bridges			√
EN 1997-1	General rules	√	√	√
EN 1997-2	Testing	√	√	√
EN 1998-1	General rules, seismic actions	√	√	√
EN 1998-2	Bridges	√	√	√
EN 1998-5	Foundations	√	√	√

Table 3 Overview of Eurocodes to be applied for bridge structures (from [27]).

As it is outlined in Table 3, in bridge construction mostly steel or reinforced concrete or steel/concrete composite structures are addressed. According to Eurocode 5, part 2 (EN 1995-2) timber bridges are foreseen but due to the material properties, costs and expected service life of a structure wood constructions are usually not considered for large scale bridges or elevated transport systems.

Traffic loads

Traffic loads are additional loads, which affect the structural design of bridge structures. Traffic loads are formulated in Eurocode 1 (EN 1991-2 – Traffic loads on bridges) in form of traffic load models. These models have been developed that they satisfy the following criteria [28]:

- Should be easy to use
- Should be applicable, independent from the span of the bridge and the static scheme
- Should be able to reproduce as accurately as possible target values and all the scenarios of traffic flow and obstructions occurring during the service life of the bridge
- Should include in the load values and dynamic magnifications due to the road-vehicle and to the bridge-vehicle interactions
- Should allow to easily combine local and global effects of actions
- Should be unambiguous, covering all the cases that could occur in the design practice

Target values of real traffic induced effects can be derived from numerical calculations or analytical methodologies. These take into consideration the initial bridge design (e.g. span of piers, number of lanes), relevant traffic data (traffic flow, density, type of vehicles, etc.) and vehicle-structure interactions (e.g. breaking, impact, fire, etc.). Calculations and analysis are based on real traffic data, assessed from the particular region/road system, where the bridge will be built.

The Eurocode 1 EN 1991-2 foresees different load scenarios. These describe the loads under different traffic situations. The scenarios are independent on the type of bridges and materials used. They include:

- Traffic load models
    - Vertical forces – Load model 1 to 4
    - Horizontal forces – Breaking and acceleration, centrifugal, transverse
- Group of loads
    - Group loads – Group load 1 to 5
    - Characteristic, frequent and quasi-permanent values
- Combination with actions other than traffic actions

Loading scenarios for vertical forces are grouped into of four load models. According to Eurocode 1 these models apply to span length shorter than 200 m (from pier to pier). For longer loaded length national annexes apply.

Load model 1 (LM1) – Concentrated and distributed loads which cover most of the effects of cars and trucks (main model – general and local verifications.

Load model 2 (LM2) – Single axle load applied on specific tyre contact areas which cover the dynamic effects of the normal traffic on short structural members (semi-local and local verifications).

Load model 3 (LM3) – Set of assemblies of axle loads representing special vehicles; those can travel on routes permitted for abnormal loads (general and local verifications).

Load model 4 (LM4) – Crowd loading 5 kN/m2 (general verifications).

The exact descriptions and entailing requirements are listed in Eurocode 1 EN 1991-2, section 4.3.2 to 4.3.5. The characteristic, frequent and quasi-permanent values for the different load models are listed in Table 4.

The code is dividing carriage ways (bridge decks) into notional lanes. The load model is then applied to these notional lanes in form of specific axle loads. Horizontal forces are addressed in EN 1991-2 in form of acceleration and breaking as well as in form of centrifugal forces in case the bridge deck has a horizontal curvature. Group loads are defined as the load models LM1 to 4 with additional loads from pedestrians, cycle tracks and horizontal loads.

Traffic Load Models	Characteristic values	Frequent values	Quasi-permanent values
LM1	1000 year return period (or probability of exceedance of 5% in 50 years) for traffic on the main roads in Europe (α factors equal to 1, see 4.3.2).	1 week return period for traffic on the main roads in Europe (α factors equal to 1, see 4.3.2).	Calibration in accordance with definition given in EN 1990.
LM2	1000 year return period (or probability of exceedance of 5% in 50 years) for traffic on the main roads in Europe (β factor equal to 1, see 4.3.3).	1 week return period for traffic on the main roads in Europe (β factor equal to 1, see 4.3.3).	Not relevant.
LM3	Set of nominal values. Basic values defined in annex A are derived from a synthesis based on various national regulations.	Not relevant.	Not relevant.
LM4	Nominal value deemed to represent the effects of a crowd. Defined with reference to existing national standards.	Not relevant.	Not relevant.

Table 4 Values for the different load models for road bridges according to EN 1991-2 (from [29]).

Fatigue load models address the frequency of loads caused by vehicles which can cause fatigue. This is in particular true for heavy vehicles such as trucks, whose can cause particular loading fluctuations due to their 5 to 10 times higher weight compared to cars. This is therefore a key aspect when considering fatigue modes when considering bridge construction. To model fatigue loads the so-called load spectrum is required. The load spectrum is defined as the load variations or the number of recurrences of each load level during the design life of a structure [30].

The Eurocode focusses on the heavy vehicles with more than 100 kN load such as trucks, when it concerns fatigue. Similar to the vertical traffic load models 1 to 4, there exist 4 fatigue models [29].

Fatigue load model 1 (FLM1): Similar characteristics as LM1.

Fatigue load model 2 (FLM2): FLM2 consists of a set of idealized trucks, called "frequent" trucks. The definition of the truck types is listed in Table 4.6 of the Eurocode 1

Fatigue load model 3 (FLM3): Single vehicle. This model consists of four axles, each of them having two identical wheels. The weight of each axle is equal to 120 kN, and the contact surface of each wheel is a square of side 0,40 m.

Fatigue load model 4 (FLM4): Set of standard trucks, which together produce effects equivalent to those of typical traffic on European roads.

The fatigue load models 1 and 2 are used for a boundless fatigue checks and the models 3 and 4 for damage computations.

Further requirements are included for minimizing structural damage in case of seismic actions. Here, the Eurocode 8 (EN 1998) is the guidance document.

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