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TRANSPORT

On the Frankfurt bridges, proprietary roadways are being created on the outer sides of the bridge surface exclusively for the 400 bridge vehicles. These vehicles can drive there autonomously or centrally controlled without interference because no other road users interfere with them. This will create the world's largest autonomous traffic system on the Frankfurt bridges.

The bridge traffic is available not only to the 35,000 bridge residents, but also to Frankfurt's citizens and visitors: over 40 million passenger trips are made by the 400 vehicles each year.

The vehicle fleet is built in modern lightweight construction, the smaller vehicles as e-cars, the larger ones as hydrogen vehicles. In order to do justice to the varied ambience of Frankfurt's bridges, large parts of the fleet are vintage car replicas from all over Europe, supplemented by ultra-modern futuristic vehicles: In this way, a traveling transport museum is being created on Frankfurt's bridges - that can be experienced live.

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Individual transport for all

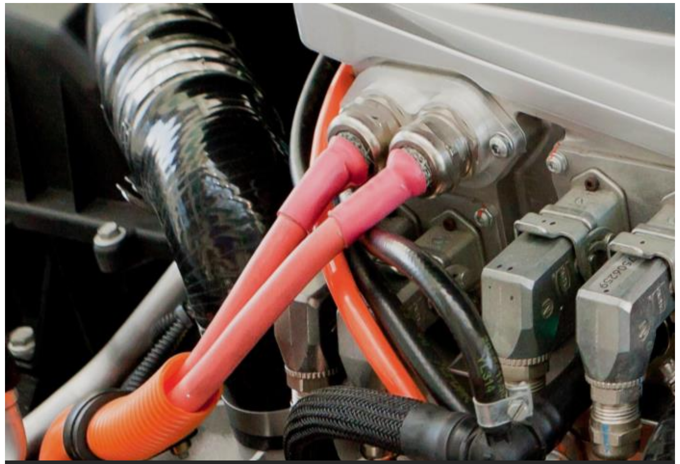
In the case of the Frankfurt bridges, all facets of an optimal transport system were considered

Autonomous driving and safety

Centrally controlled traffic shortens waiting and travel times, reduces braking with tire abrasion and prevents accidents

Vehicle fleet: Modern classic cars

Centrally controlled traffic shortens waiting and travel times, reduces braking with tire abrasion and prevents accidents



Sustainability through technology

On Frankfurt's bridges, vehicles powered by hydrogen and electricity completely replace internal combustion engines

A vehicle concept in detail

Buses, trains and cars arrive directly when needed, waiting times are eliminated, journeys are quiet and relaxed

Logistics & Vision

Buses, trains and cars arrive directly when needed, waiting times are eliminated, journeys are quiet and relaxed

Individual Transport for All

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In the case of the Frankfurt bridges, all facets of an optimal transport system were considered

Around 400 vehicles can not only beautify Frankfurt's bridges and delight residents with their smart appearance, but also provide passengers with an adequate substitute for their personally owned cars thanks to their exceptional comfort. With the traffic model on the Frankfurt bridges, autonomous driving, sustainability, multifacetedness and, last but not least, punctuality and reliability in local passenger transport can be combined.

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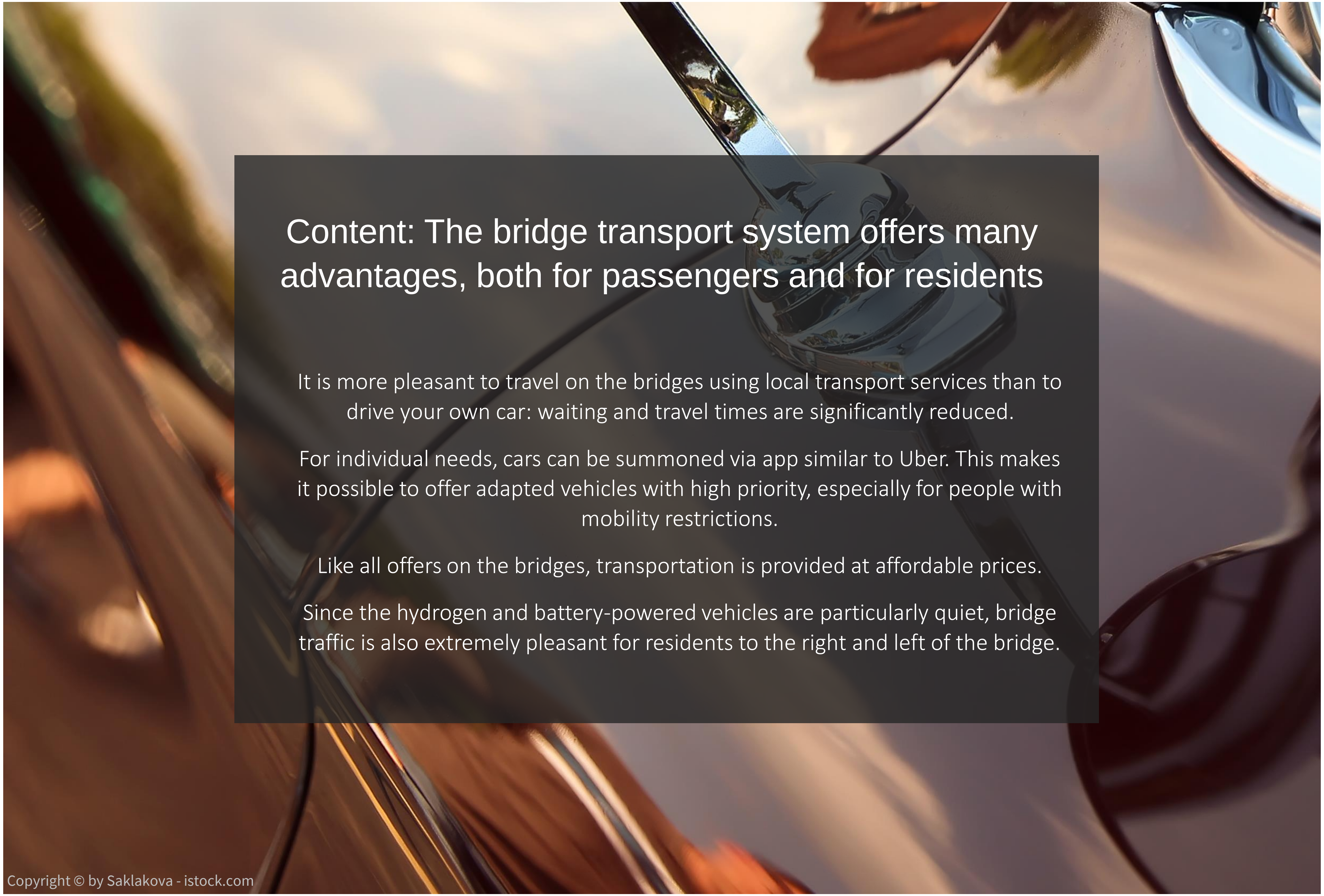

Content: The bridge transport system offers many advantages, both for passengers and for residents

It is more pleasant to travel on the bridges using local transport services than to drive your own car: waiting and travel times are significantly reduced.

For individual needs, cars can be summoned via app similar to Uber. This makes it possible to offer adapted vehicles with high priority, especially for people with mobility restrictions.

Like all offers on the bridges, transportation is provided at affordable prices.

Since the hydrogen and battery-powered vehicles are particularly quiet, bridge traffic is also extremely pleasant for residents to the right and left of the bridge.

Getting to your destination better and more comfortably with buses and trains than with your own car

Around 200 autonomous buses and streetcars and almost 100 cars provide a local transport experience on Frankfurt's bridges that beats your own car by far in terms of comfort and environmental compatibility.

You call up a vehicle tailored to your needs via an app and wait just a few minutes until you are "picked up". Everything works reliably, on time, smoothly, comfortably and cleanly.

Buses and trains arrive "on demand" instead of strictly according to schedule

Autonomous transportation offers numerous other advantages: Waiting times at stations are shorter, because there are no more schedules, the vehicles come "on demand." For one thing, you can enter where you want to go at the station - the system processes and serves this demand immediately. But you can enter in your app, while still sitting at the breakfast table, that you want to walk to the next station in 10 minutes and where you want to go - the system will then send a vehicle precisely when you arrive at the station. Or, you can share your location and the system itself will know when you will be at the station. In addition, the system is self-learning. If you leave for work every morning at about the same time after breakfast, then the system does a kind of "prearrangement": it knows how many people are leaving at what time from this station to a certain other station. What is particularly convenient is that, despite a lower maximum speed, you get to your destination faster and that the driving style is smooth, because there are no more surprises and traffic jams caused by other, individually controlling road users.

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The travel time in local passenger traffic on the Frankfurt bridges can be optimally used

Read, work and relax on the phone, chat with friends or simply look out the window instead of getting worked up at the wheel about a traffic jam, other drivers or a lack of parking spaces: That's the advantage of driving on Frankfurt's bridges.

On the bridges there is no pointless extension of travel time by stopping at empty stations

The "On Demand" system instead of timetables allows buses and trains to be called via a special app. Those who don't have a smartphone at hand can also order the vehicles via request buttons at the stations. This means that vehicles only stop at stations when passengers are boarding or alighting.

No pointless waiting at stations for bus or train - you enter your "on demand request" already on the way to the station

Users can tell the system when they need transportation as soon as they leave home: as soon as they enter the start and end stops, the system calculates which connections are needed.

Stations are placed on the bridges at intervals of 100 to a few hundred meters: you have correspondingly short distances from any point on the bridge to the next station

There is a station every few hundred meters. This is the only way to make autonomous transport an acceptable substitute for individual transport: sometimes you park your car 100 or 200 meters away.

For even more convenience, individually autonomous cars can also be called via app.

Those who still prefer to travel in an individual car can simply call up an autonomously controlled individual car via the bridge app. This, too, is a component of the bridge's local public transport system. Like the buses and trains, these vehicles have a particularly colorful and unusual design.

Transportation on the bridges adapts individually to the needs of passengers

Car - Because you are in a hurry and want to get directly to your destination, because you are traveling with luggage and need a lot of storage space, or simply because you prefer to travel alone rather than with strangers, you sometimes need a personal vehicle. The cars are adapted to the various needs and depending on your mood and needs, you can call the right car for a small extra charge via the bridge app, similar to a cab or Uber, but much cheaper.

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In the future, you don't necessarily have to own a car

For many people, cars are not just a means of transportation. They are an expression of an attitude to life or carry memories with them.

The Brückenflotte makes up for this by having cars for every mood and occasion in its fleet: so you can go to the swimming lake with your friends in a Bully, to the opera in an elegant vintage car or to the club evening in a UFO.

Whether you want to take your bike or your pet - there are vehicles for every need

The bridges have bike lanes on the west arm: once you get to the downtown ring, you can call a "bike vehicle".

Special carts for pet owners also make it possible to quickly take the cat or dog to the vet or arrange to go for a walk in the city forest.

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A special service concept for special needs: Accessibility, strollers, dogs, luggage and bicycles - there is a transport service for everyone

For people in wheelchairs, parents with small children or strollers, or even for passengers with knee problems, for example, there are a variety of special vehicles that make getting on and off extremely easy. There are only a few of them in vintage look, but for all vehicles of this kind, no limit was set to creativity.

Not only less waiting time but also a 75% faster transport service for people with disabilities are the goal

This means that if other passengers have to wait 6 minutes for a vehicle during peak times, for example, people with reduced mobility receive their desired vehicle after just one and a half minutes. Automatic prioritization of these vehicles by the control computer also makes it possible to achieve faster transport services: All vehicles with passengers requiring accessibility have priority over other vehicles in bridge traffic. Only the fire department, ambulances and other emergency vehicles enjoy an even higher priority.

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Many classic cars are converted for use as barrier-free vehicles

Futuristic vehicles in particular can be designed to be barrier-free from the outset - the flower boxes on this barrier-free creative vehicle need to be watered and maintained at night in the maintenance loops at the ends of the bridge

But people with walking disabilities or in wheelchairs can also use all the other classic cars on Frankfurt's Bridges for adventure rides: with the help of the operator kiosks

Unfortunately, historic vehicles are usually not equipped to be barrier-free, and in everyday traffic it is beyond the scope of personnel to keep qualified assistants on hand in case people with walking disabilities want to board. On the Frankfurt Bridges, people in wheelchairs or with other impairments find it more pleasant anyway to travel in the specially designed, preferentially and quickly arriving vehicles in pure everyday transport, when they want to get from A to B quickly. But if they want to make an experience journey with one of the old-timers, they need to announce it only at one of the operator kiosks: They are in contact 24/7 with all bridge personnel and ensure that staff and auxiliary equipment are available at the registered times to make it possible for people with walking disabilities to get on and off the train - similar to Deutsche Bahn.

The bridge pass: access for all

For more people to use public transport, it has to be affordable. Especially for people with less money. That's what the Brückenpass was designed for (which is also available as a bridge app with QR code)

Transportation on the bridges - luxury at affordable prices

For about 25 euros a month, anyone living in Frankfurt and the surrounding area can buy a bridge pass, on which, among other things, the ticket to the bridge traffic is loaded (on the bridge pass can also be loaded other services -> Buildings&Bridges). Pensioners, students, unemployed and other needy people pay only half.

The bridge pass entitles them to ride the bridge passenger service as often and as long as they wish. It does not matter whether they use the buses or trains.

Important: The bridge itself is free of charge. You only need the ticket if you want to use the local transport.

The bridge transport system offers many advantages not only to passengers but also to local residents: Because they have an extra transport service on their doorstep, which is also exceptionally quiet

Bridge traffic is not only pleasant for passengers, but also for local residents. Since both hydrogen and battery vehicles run electrically, they are: quiet. In addition, the vehicles do not have to drive over curbstones manhole covers and other elevations as they do in the city. They move on almost perfectly flat asphalt most of the time. Residents can therefore enjoy the many colorful and unusual vehicles on the bridges without having to hear them.

The biggest advantage, however, is that they now have a transportation option right outside their front door that allows them to get to other parts of the city that were previously difficult to reach or required multiple transfers.

The roadway of the future will not only be level and pleasant to drive on, but will also be planted with vegetation in the center of the roadway.

In the city of the future, roadways will be greenable in the middle, since autonomously centrally controlled traffic will eliminate overtaking maneuvers and vehicles will travel in their lane over long distances, so that - similar to rails already today - the middle section of the roadway will be greenable within the minimum wheelbase.

Demarcation from pedestrians walking along beside the roadways is accomplished either by aesthetically appropriate railings or also by shrubs and bushes that can be planted along the street in the parking spaces that are eliminated.

The vision

- If autonomous traffic with low maximum speeds achieves the same transport performance through intelligent control as vehicles traveling twice as fast today and
- when the risk of accidents is drastically reduced by the lower maximum speeds and autonomous control;
- if everyone always has a vehicle drive up only when they need it, and
- when automated maintenance processes as well as significantly fewer accidents mean that the vehicles hardly suffer any damage,

then fewer newly produced vehicles will be needed - in return, correspondingly more effort can be put into the individual vehicle. This in turn can lead to a new design world in which vehicles represent a genuine cultural enrichment of life.

The bridge traffic system not only offers benefits to direct users, but also serves as a model for traffic in the city of the future

On the Frankfurt bridges, the use of vehicles that "drive up" on demand immediately, cheaply and safely can be experienced in an exemplary manner and accelerate the change in behavior among the population that has already begun: already today, car-sharing is enjoying ever greater acceptance, even if it is still associated with many disadvantages. This may change in the future as a result of a world with autonomously driving vehicles: Because for many people, other things on their doorstep are already more important than their own car. And if, in the future, the right autonomously driving car always pulls up at the push of a button, as if with a chauffeur, and you no longer need your own - only then will fewer parking spaces *really be* needed.

The freed-up areas can be planted with planters, beds and, of course, trees or used by "urban gardening" enthusiasts. The cityscape is changing

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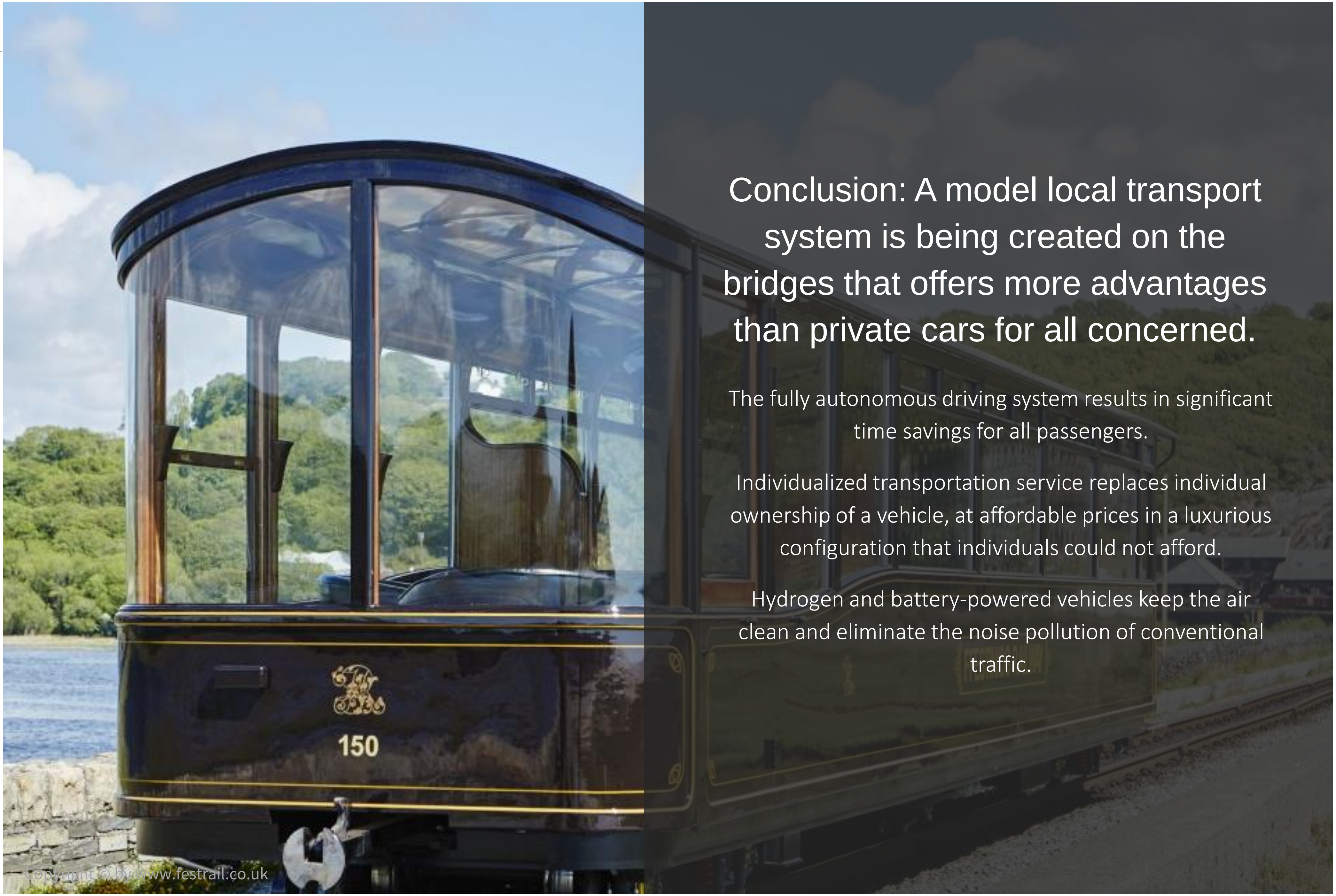

Conclusion: A model local transport system is being created on the bridges that offers more advantages than private cars for all concerned.

The fully autonomous driving system results in significant time savings for all passengers.

Individualized transportation service replaces individual ownership of a vehicle, at affordable prices in a luxurious configuration that individuals could not afford.

Hydrogen and battery-powered vehicles keep the air clean and eliminate the noise pollution of conventional traffic.

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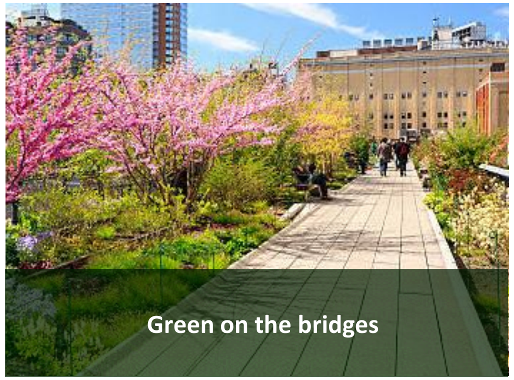
Green on the bridges


Unsealing of the city center


The Master Academy

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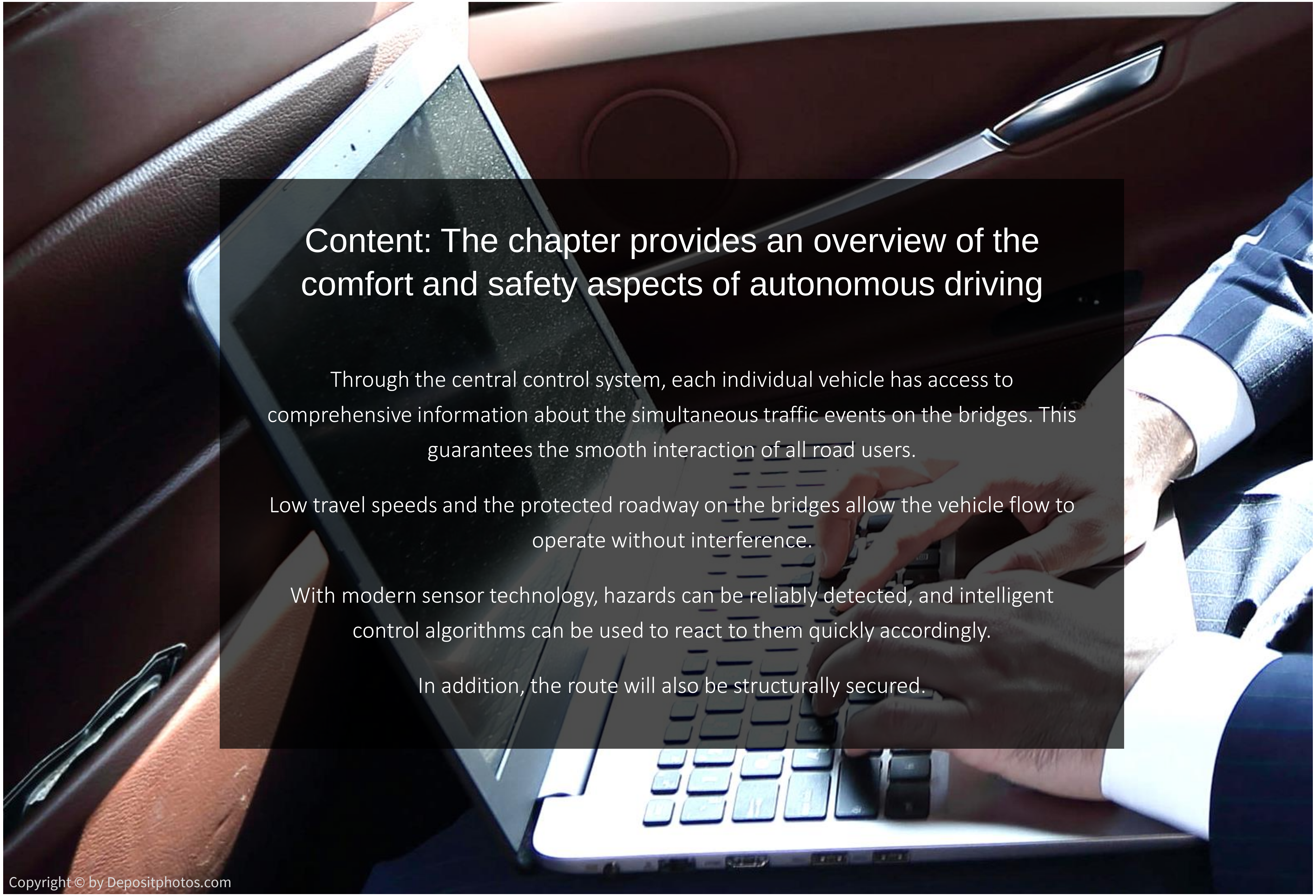
Autonomous Driving and Safety

Autonomous driving on the bridges is extremely safe and thus enables relaxation while driving

Today, mass transit is usually associated with stop-and-go, a view of traffic lights and other cars, and exhaust fumes. The autonomous system on the bridges makes all this disappear and allows for an environment characterized by beautiful buildings, extensive planting and a safe and gliding ride experience. A self-learning control system and additional safety mechanisms guarantee an exhilarating transportation experience.



Content: The chapter provides an overview of the comfort and safety aspects of autonomous driving

Through the central control system, each individual vehicle has access to comprehensive information about the simultaneous traffic events on the bridges. This guarantees the smooth interaction of all road users.

Low travel speeds and the protected roadway on the bridges allow the vehicle flow to operate without interference.

With modern sensor technology, hazards can be reliably detected, and intelligent control algorithms can be used to react to them quickly accordingly.

In addition, the route will also be structurally secured.

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All vehicles on the Frankfurt bridges are controlled centrally: they are all integrated into a common fleet information system

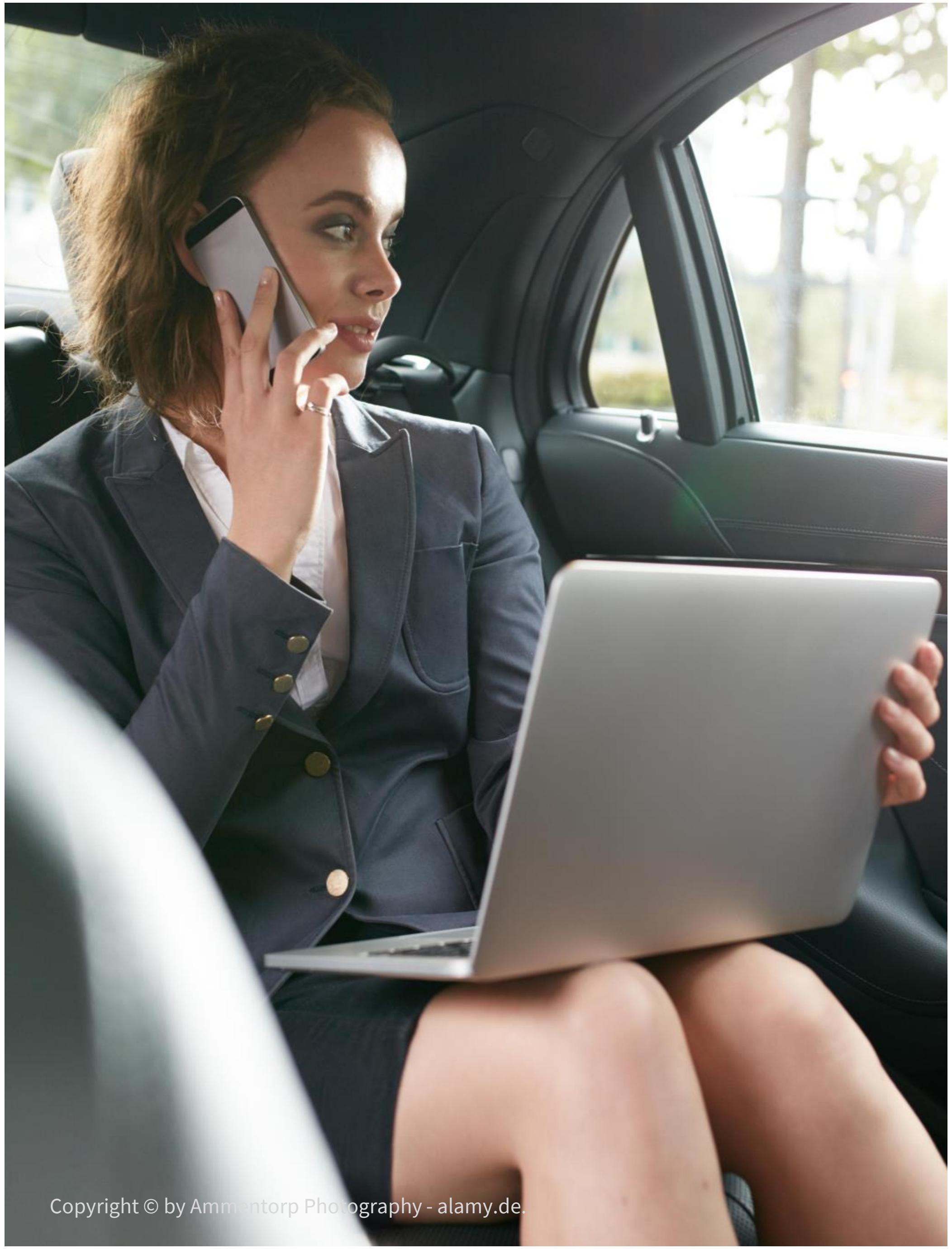
Since all vehicles are controlled by a central computer and no longer by their own steering wheel, this computer is always aware of the positions, speeds and next maneuvers of *all* vehicles. It also receives information about any obstacles along the route via cameras, even before the vehicles can detect them.

As a passenger you glide quietly along on the bridges

By driving with foresight, braking and acceleration can be made smooth and largely avoided.

For passengers, this makes the ride particularly pleasant: they glide along smoothly and can read, work or simply gaze dreamily out of the window.

Since all vehicles are equipped with free wifi, the driving time can be used as well as if you are chauffeured by a calmly driving professional.



Autonomous driving is one thing above all: extremely safe!

When it comes to autonomous driving, there is always one question: Is it safe? Can computers be trusted?

The answer is yes. Precisely because the system is 100 percent computer-controlled and the route, vehicles and controls were designed together, it is safer than conventional driving with the self-driven vehicles.

Analyses show time and again that the most frequent cause of accidents is human error. This can be eliminated by a computer system with multiple safeguards.

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Stop speeding

All bridge vehicles can travel at a maximum speed of 30 km/h - the average is 17.8 km/h.

Nevertheless, on many routes through Frankfurt they get from A to B faster than with conventional traffic, because there is no need to stop at traffic lights, and they only stop at stations where someone wants to get on or off.

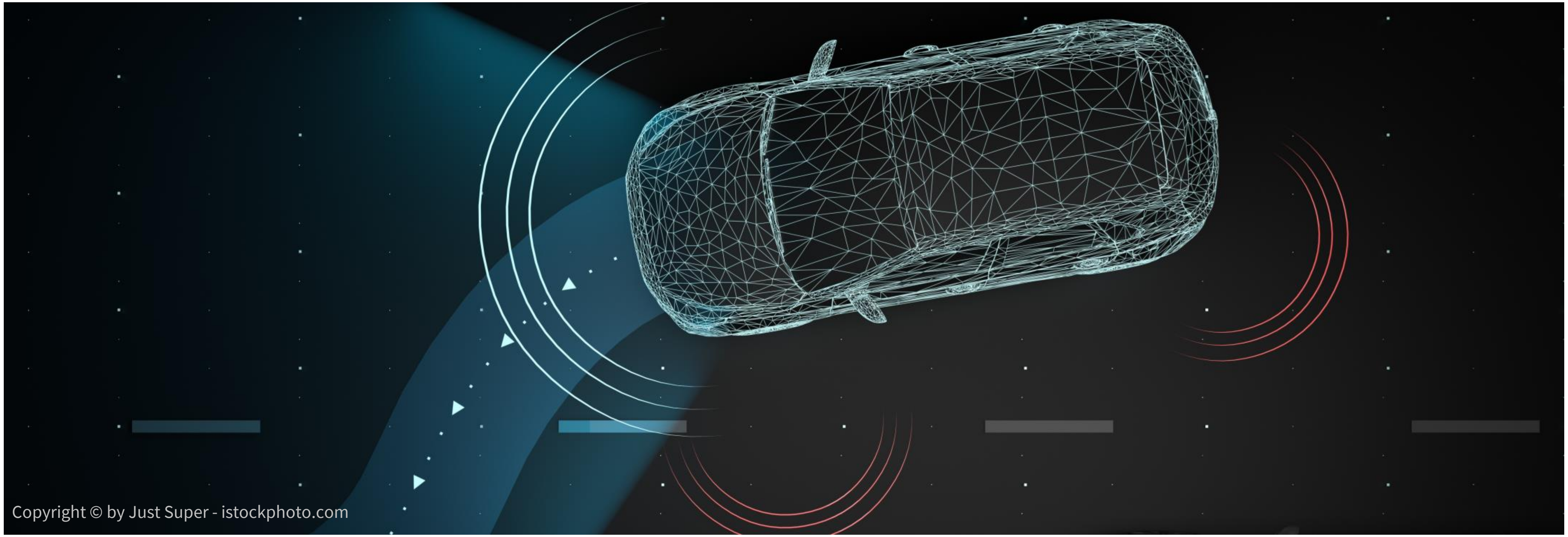
Each vehicle can thus choose the optimal routing at any time to reach its destination faster.

What's more, on Frankfurt's bridges, the autonomously driving vehicles move in a protected "biotope," as it were. The separation of the pedestrian path and the roadway by guardrails allows for trouble-free traffic and means more safety for people (and animals). Crossing the roadway is possible at special, secured crosswalks. There are emergency gates in the railing every few meters - but these can only be used for emergencies when passengers exit in the middle of the track.

A wide range of sensors are available for autonomous vehicles for comprehensive "perception" of the environment

Another frequently asked critical question is: How well does an autonomously driving vehicle really perceive other vehicles, pedestrians or other environmental elements? What if the sensors of such a vehicle fail? A living person at least always has his or her eyes open when driving - at least one hopes so. And as long as the person driving is really looking at the road, has no visual impairment and is not too distracted, he or she will always see and possibly hear everything. But a remote-controlled vehicle?

Well, here again, autonomous driving vehicles are superior: they have not just one organ of perception or two or three, but quite a few . . . . .



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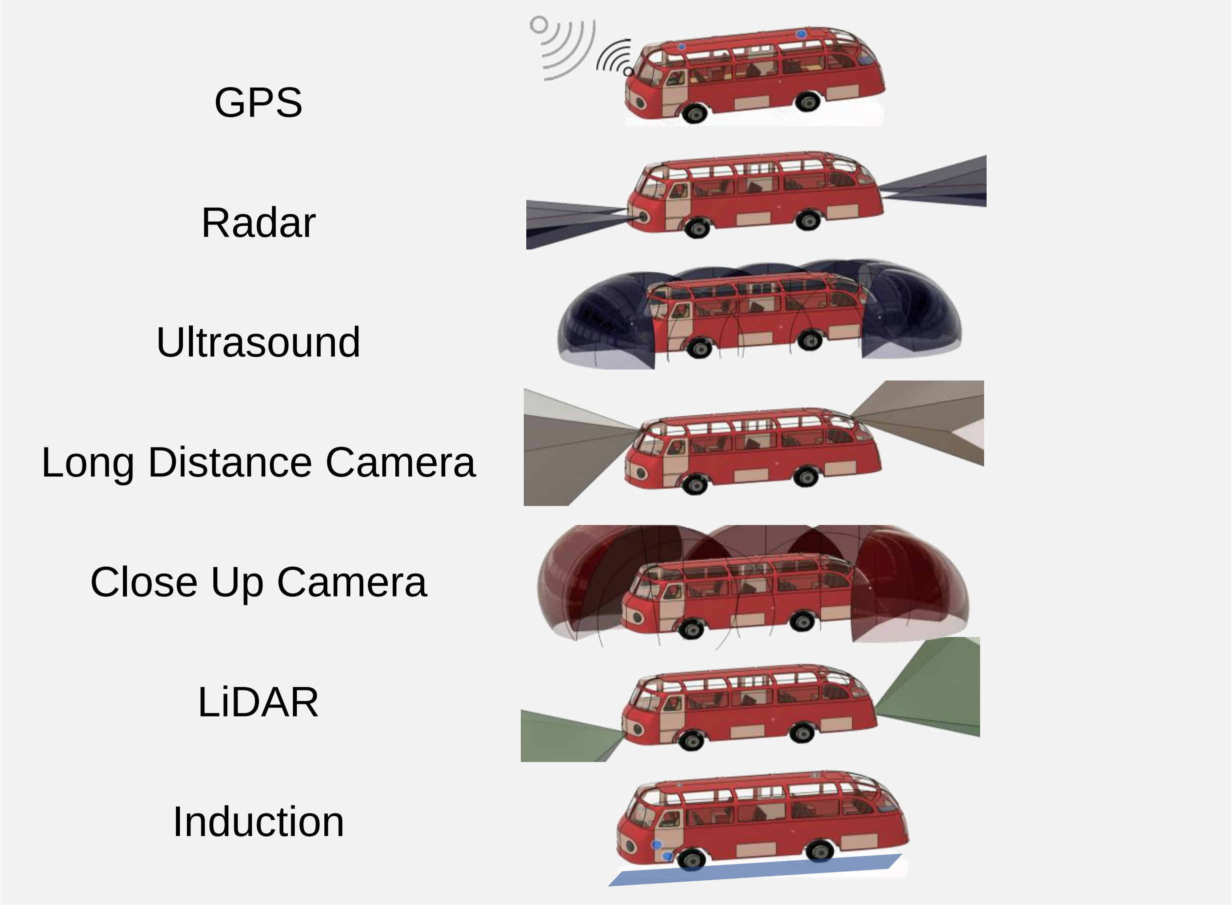
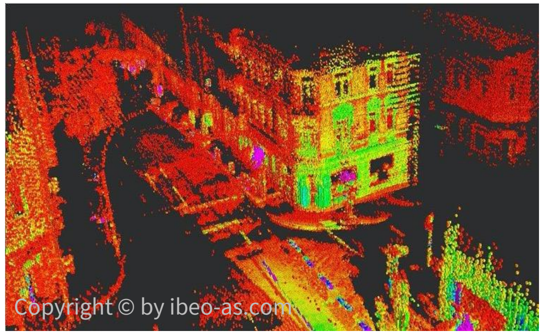
Autonomously driving vehicles have more "sensory organs" than humans in order to also perceive 100% everything in time - the car therefore "sees" more



There are 8 "sensory organs" in the bridge vehicles, which use various measuring methods to detect their surroundings. In combination with extremely fast data processing, the reaction speed of a human being is significantly exceeded.

State-of-the-art sensor technology is used in the autonomous driving systems on Frankfurt's bridges

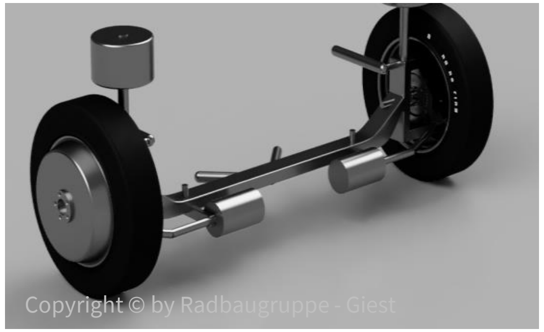


Lidar

The environment can be scanned and mapped three-dimensionally using a LIDAR sensor. A laser source emits pulsed light waves that are reflected by objects and detected by the sensor when they return.

Induction

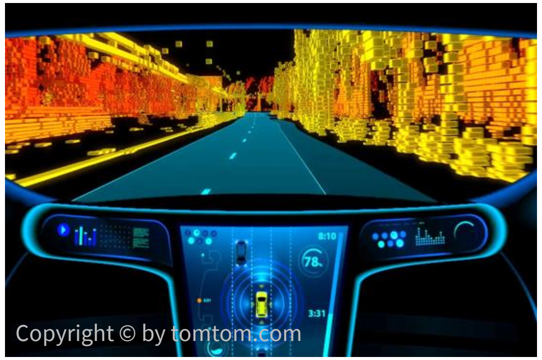
A conductor installed on the road is detected by a magnetic field emitted by the vehicle on the ground. This is a safety-related measure for determining position in poor visibility.



Odometry

Odometry can be used to determine the position and orientation of a vehicle based on data from the drive system.

In den autonom fahrenden Fahrzeugen auf den Frankfurter Brücken kommt modernste Sensorik zur Anwendung

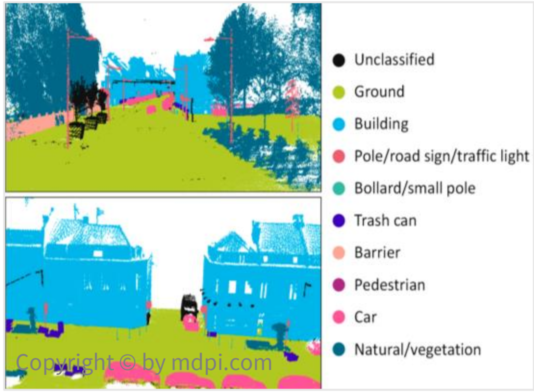


Positions- und Bewegungsbestimmung

Mit Hilfe von GPS, Kamera, RaDAR und LiDAR kann das Fahrzeug seine absolute Position auf den HD-Karten der Brücke ermitteln. Mit diesen Informationen ist es möglich, die weitere Route zu planen, Daten über Hindernisse zu verarbeiten und vorrausschauend zu fahren.

Pfadplanung und Aktor-Regelung

Mit Hilfe der Kameras, des Ultraschalls, der Induktion und der Odometrie hält das Fahrzeug seine vorgegebene Position auf der Strecke. Außerdem lassen diese Sensoren schnelle Reaktionen auf unvorhergesehene Ereignisse und Hindernisse zu.



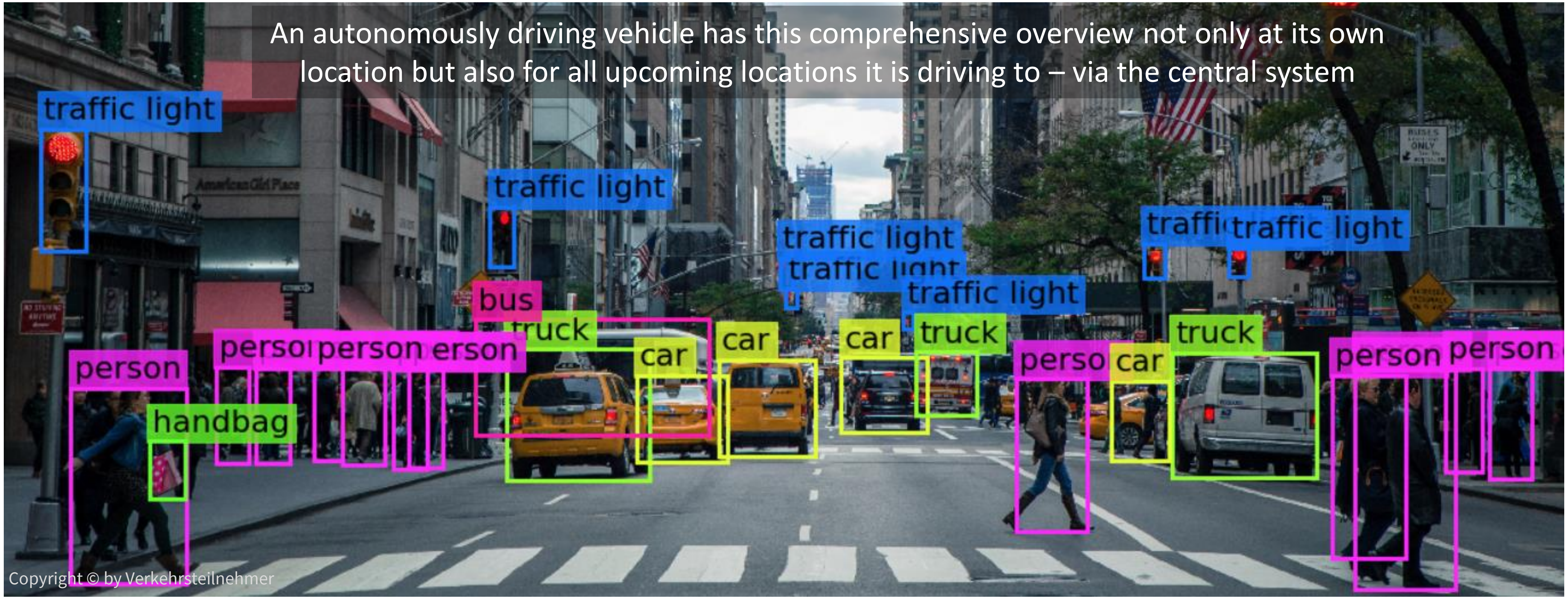
Objekterkennung und -klassifizierung

Durch Kameras, LiDAR und RaDAR kann das Fahrzeug Objekte im Fahrbereich erkennen und klassifizieren. So ist es möglich zu unterscheiden, ob dort eine Person oder eine Kiste auf der Strecke liegt und entsprechende Maßnahmen einzuleiten.

Die umfassenden Sensordaten müssen interpretiert und übersetzt werden

Die Sensordaten erfassen die Umgebung in einer abstrakten Form. Zur Durchführung der Fahrt müssen aus diesen Daten verschiedenste Informationen berechnet werden. Beispiele hierfür sind die Bestimmung der eigenen Position in der Stadt, die Planung der Route zum Ziel, die Antizipation der Bewegung anderer Verkehrsteilnehmer, die Erkennung und Klassifizierung von Objekten sowie die Planung der nächsten Schritte.

Während der menschliche Fahrer in Bezug auf die Blickrichtung, die verfügbaren Spiegel und die Multi-Tasking-Fähigkeiten stark eingeschränkt ist, kann das autonome Fahrzeug auf die individuellen Stärken der verschiedenen Sensortypen zurück greifen und so alle diese Aufgaben simultan, schnell und in 360° Rundumsicht erfüllen.



Even if "visibility" is poor, the vehicles and their control center can still perceive everything

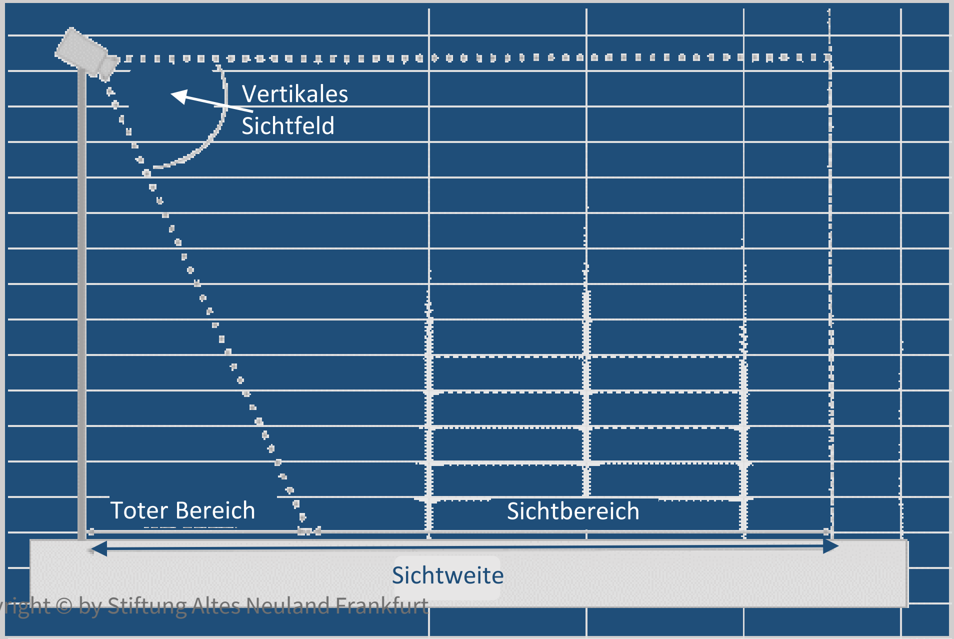
Via induction, GPS, and pre-programmed trajectories as well as other sensors, the vehicles always get a picture of their surroundings; even at night, in rain, fog, or ice and snow.

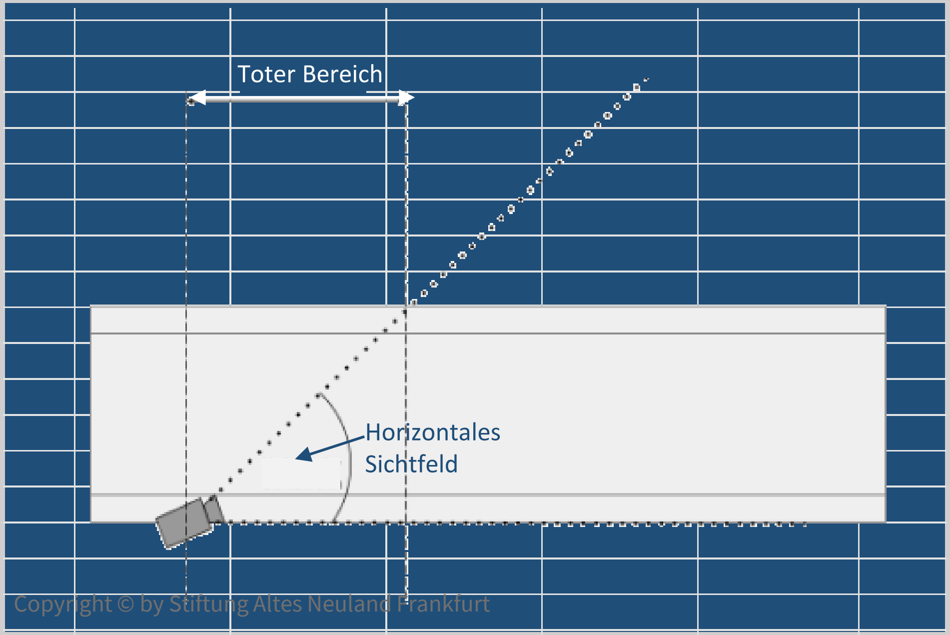
All measurement data is forwarded to the control system in real time. There are therefore no unforeseen driving maneuvers, as occur in regular road traffic. All driving movements are coordinated, and the system drives with foresight.

In addition, the control center receives camera information about the entire route

Not only the vehicles, but also the track itself has sensors. Cameras are installed at the edges of the track to monitor the road at all times. If, for example, a child is spotted on the track, the autonomous vehicle approaching it knows about it before it is in sight.

With the help of the cameras' viewing angles, the camera network along the route was selected to be so close-meshed that no danger remains undetected. Around 35 cameras are needed per kilometer of track for each lane. The data processing of the camera images takes place in the so-called supply centers along the route.





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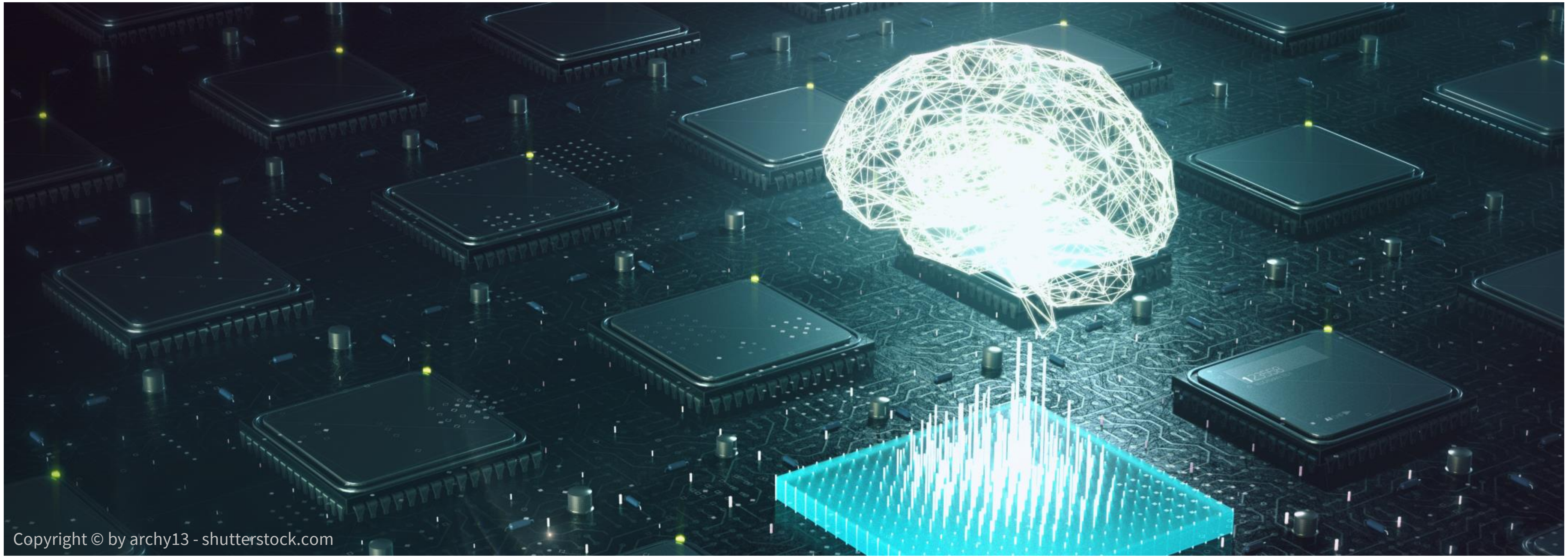

In conventional road traffic, the main problem for autonomous vehicles is how to respond to random human and animal behavior

The vehicle, of course, cannot assess the condition and spontaneity of a passerby - it simply stops when anything, human or animal or otherwise, even approaches it.
The main problem with autonomous driving vehicles is not that they are more likely to run over something, but quite the opposite: that they stop immediately upon sighting the smallest potential obstacle.

On the bridges, this is largely avoided by the specially protected driving sections: people only have free access to the roadway at the stations and thus only there the possibility of bringing the vehicles to a standstill by erratic behavior.

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On the Frankfurt Bridges, the vehicles have the advantage that they travel on proprietary routes shielded from other road users and thus act particularly safely

As soon as autonomous driving is transferred to city streets, the routes there will have to be "secured" as well: The slimmest option for this is guardrails

Not only boring standard railings should be used, but preferably pretty appealing designs should be brought to bear: Because if you imagine these railings on all the streets of a city, then a pleasant appearance is extremely important. There can be crossings for pedestrians every 10 to 20 meters, but the rest of the roadway must be demarcated, because autonomous driving cannot be implemented as an overall traffic system without safeguarding the road.

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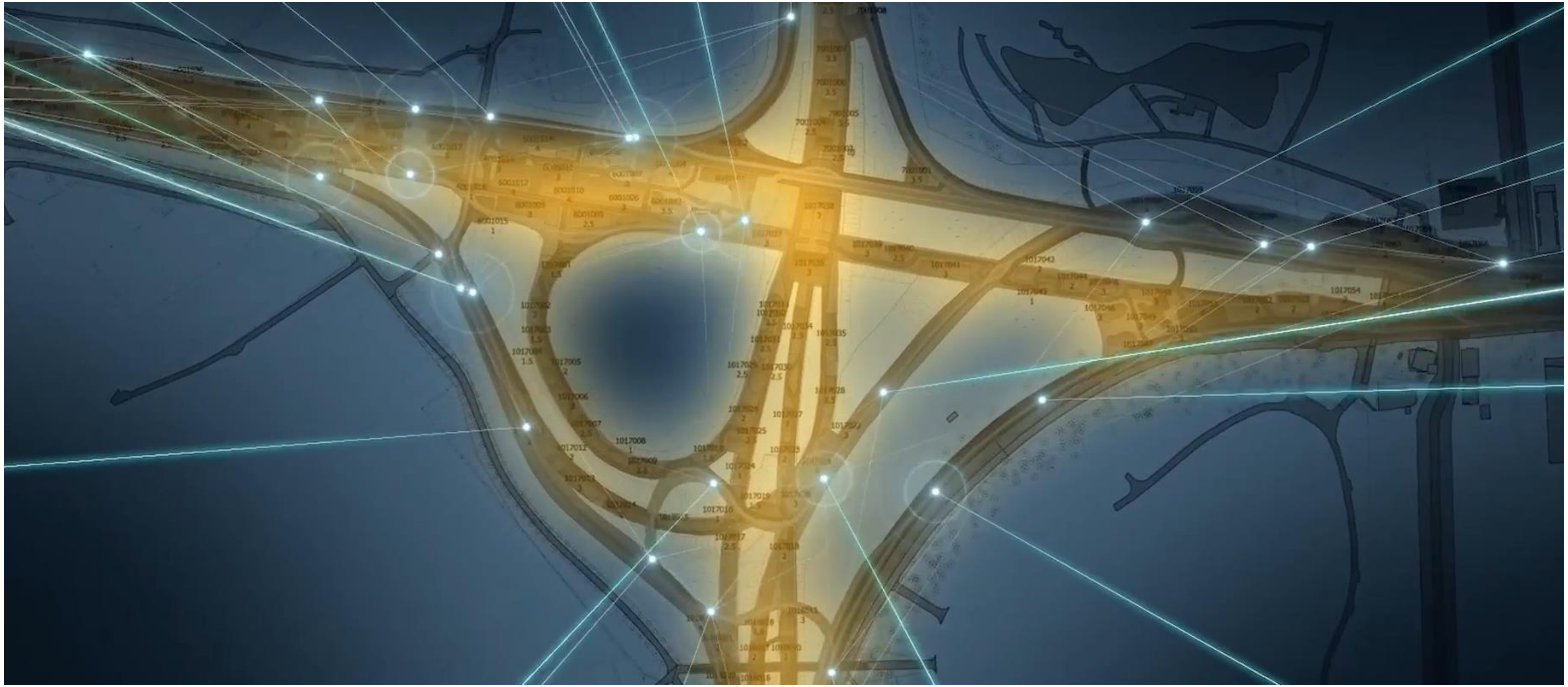
With plain railings, planters can serve as a softener

Plants in planters along the roadside should be ground based and have water storage layers in the clay pots to keep them well maintained without a lot of manpower.

In terms of design, you can get ideas for planter boundaries to the roadway from the countless enclosures that restaurants make for their outdoor areas facing roads.

Autonomous driving systems still need to be further developed in order to optimize them logistically. This will require a larger complex traffic network, such as that represented by the Frankfurt Bridges



Once such systems are so well developed that they can offer people individualized transportation services instead of individual car ownership, studies show that the number of vehicles on the road will be reduced by more than 80 percent

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If there is more space at the roadside because autonomous driving systems require fewer vehicles and thus fewer parking spaces, but at the same time all lanes have to be secured, then former parking spaces can also be planted with hedges or low shrubs at the roadside as a safeguard.

With even more space along the streets, so-called "parklets" can also be created

The reduction of cars through centrally controlled autonomous vehicles leads to more space for green in our inner cities and also creates new experience spaces: the "Parklets". These can be designed in completely different ways. And since engines will be largely emission-free and quiet, sitting by the road will then also be fun.

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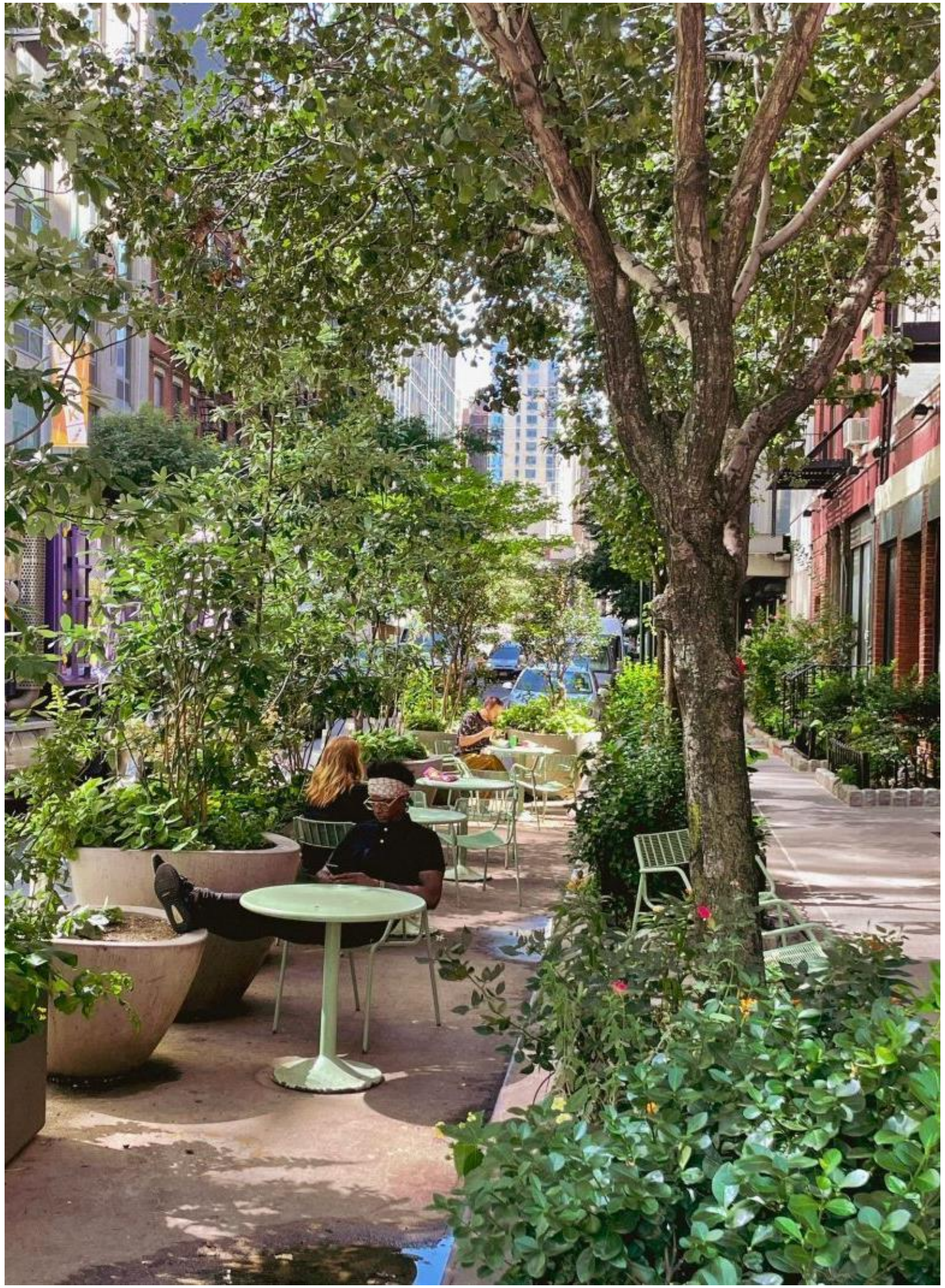
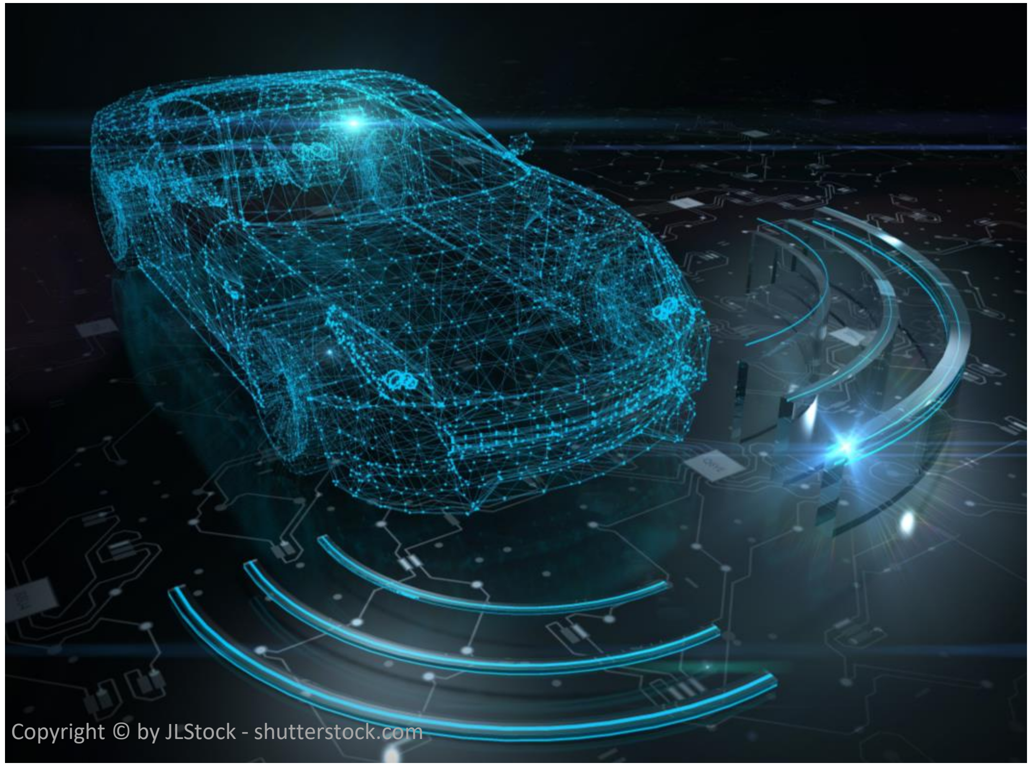


Before...

Autonomous vehicles react significantly faster than humans to unforeseen events in traffic or in their environment

If something unforeseen does happen, the system reacts in fractions of a second, faster than a human could. At the same time, the driving behavior of all other vehicles is automatically adjusted. They slow down, choose a different route or pull into a lay-by to make way for any emergency vehicles. Unexpected emergency braking and evasive maneuvers are therefore (virtually) non-existent.



So far, about one third of microplastics in Germany comes from tire wear: Since autonomously driving vehicles have significantly fewer and slower braking processes, they also release significantly less microplastics into the environment

So far, there are only routes with autonomously driving vehicles that drive a certain way back and forth on their own lane. However, in order to be able to convert future urban traffic completely to autonomously driving, centrally controlled vehicles, large test routes are needed, such as the Frankfurt bridges. Only through live application can such a highly complex system be developed.

But the effort is worthwhile, especially with regard to nature and future generations: More and more microplastics are being released into nature and from there enter our organisms. Usually, we think of plastic in the sea as the main source of pollution. But in Germany, one third of the microplastic that enters the environment comes from tire abrasion. With the help of central systems for brake-reducing control of all vehicles, at least this largest source of microplastics in Germany can be significantly reduced.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On the bridges, railings and masonry provide additional safety for people and animals

It may be able to perceive a pedestrian eight times over, but can it judge whether the pedestrian is brave enough to run across the street in front of it?

Therefore, on one side the roadways are separated from the sidewalks by decorative railings. On the other side of the lanes are natural meadows, to which only a small wall protects against small animals. The vehicles thus drive completely undisturbed by people and animals.

If someone does make it onto the roadway, the autonomous vehicles are equipped with safety sensors and apply the brakes.

Another safety factor: Vehicles cannot deviate from the lane and are stabilized by the roadway shape

The lowering and shape of the lanes ensure that vehicles do not stray from the path.

The vehicles, which only travel at a maximum speed of 30 kilometers per hour, are thus prevented from going off the tracks under their own power thanks to a 35-cm-deep lowering of the track.In addition, the road surface is concave in shape, which automatically stabilizes the vehicles in the middle.

Furthermore, the lanes are separated from the sidewalks in many cases by a 10-centimeter-high plinth to which a decorative railing is attached. Thus, vehicles cannot drive onto the sidewalk, nor can pedestrians unintentionally enter the roadway.

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As a further safeguard, bollards are installed at all Curves of the bridge route provided

At curves, bollards about one meter high are additionally embedded in concrete to prevent passengers from jumping out of the troughs. however, these bollards have more of a psychological function: they show passengers that everything is being done to ensure their safety.

As a further safeguard, bollards are installed at all Curves of the bridge route provided

And in the first years there are still bus and train attendants - so that everyone feels well looked after at all times

Autonomous driving is unusual. A bus without a driver, a streetcar without a female driver? Currently, this would be rather frightening for most people. That's why bus and streetcar attendants will always ride along on the Frankfurt bridges in the first few years. They serve as contact persons; answer questions, show how to use the app, and help with uncertainties and anything else that comes up. For seniors in particular, it is important to have someone they can turn to with their questions.

The roadway on Frankfurt's Bridges always remains in perfect, safe condition

The protected character of the traffic routes on the bridges means that the roadways are always in good condition.

There are no environmental influences such as the deformation of the pavement of the roadways by tree roots, since no trees or only plants suitable for the bridge structure are planted on the bridges.

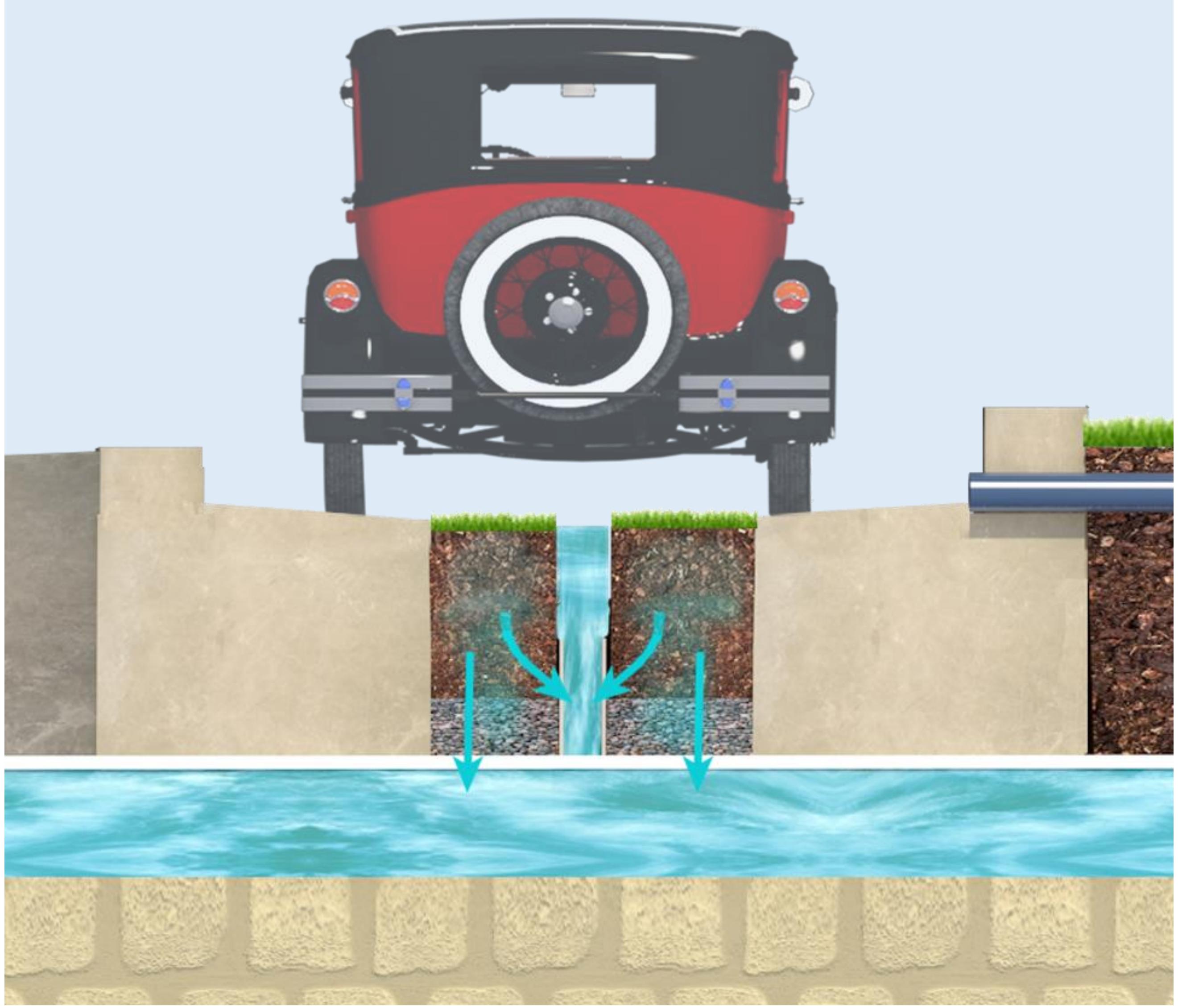
Since there is a geothermally heated system under the roadways and frost thus cannot damage the road surface either, the roadway remains level and the ride with the vehicles on the bridges almost vibration-free and extremely quiet.

The roadway on the Frankfurt bridges is level, collects irrigation water and remains frost-free and safe to drive on even in winter

The roadway on the Frankfurt Bridges has a rainwater collection system, which provides additional irrigation water for the plants on and next to the bridges.

In addition, a thin metal strip is integrated into the roadway with the wastewater grid strip, which is used by the autonomous system for navigation.

Through a sophisticated network of water pipes running underneath the roadway, excess geothermal energy is used in winter to keep the road frost-free at all times.



Safety and comfort go hand in hand: the central control system optimally adapts the speed of the vehicles to the course of the road for every meter traveled - thus reducing the risk of accidents to almost zero and increasing comfort, as passengers do not get dizzy on curves

On the Frankfurt Bridges, the central system optimizes the speed of the vehicles in the curves so that the lateral acceleration is always below 1.5 m/s2. This is possible without any special effort because the central control system knows the exact nature of all curves. Acceleration (to a maximum of 30km per hour) only takes place on straight stretches.

This ensures maximum safety, but at the same time increases comfort: when driving a car on curvy roads, some people quickly become nauseous. This happens because the driver of the vehicle enters the curve at high speed or accelerates when leaving the curve. The occupants thereby experience a high, so-called lateral acceleration.

Experience shows that passengers in conventional local passenger transport are exposed to maximum lateral accelerations of approx. 2.0 - to 2.5 m/s2 . As the vehicles on the Frankfurt bridges reach their destination comparatively quickly when optimally controlled, high speeds or accelerations on curves are unnecessary.

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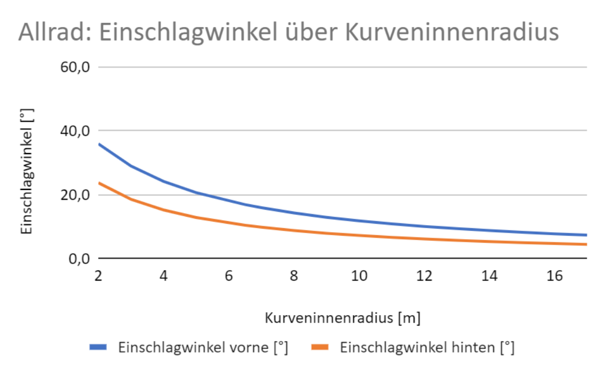
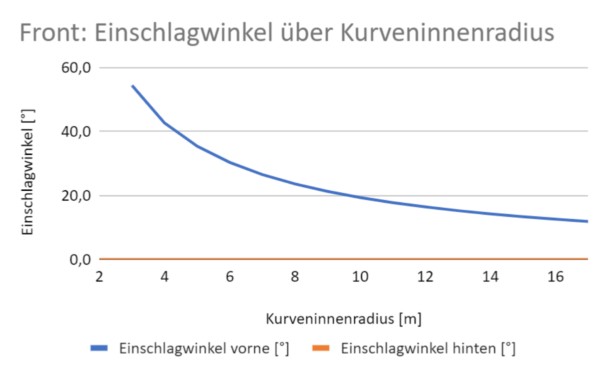
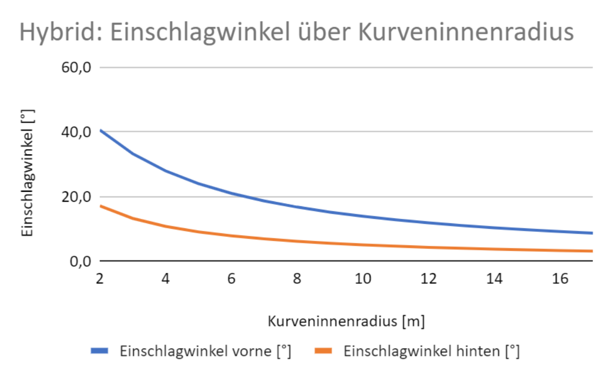
In order to exploit all the advantages of possible steering concepts for the best possible and space-saving routing on the Frankfurt bridges, various steering concepts were compared

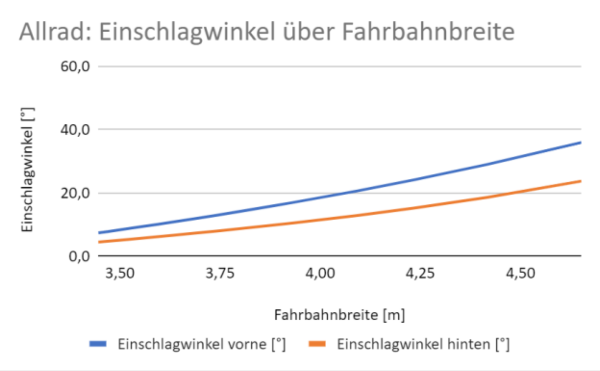
Usually, vehicles are steered by steering the front axle. However, it is also possible to steer the rear axle as well in order to negotiate tighter and narrower curves.

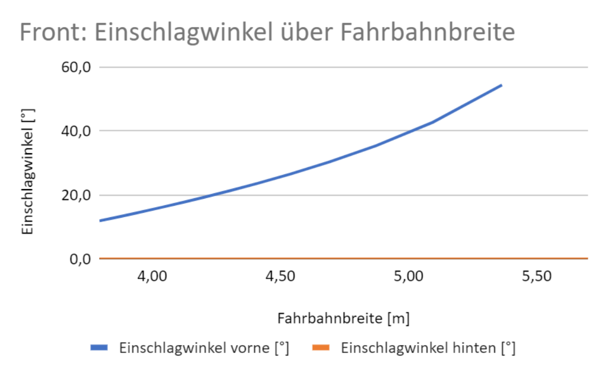
For maximum driving comfort and ease of steering, vehicles use hybrid steering, which has a steering ratio of 0.7 between the front and rear axles. The influences of the steering angle on the inside radius of the curve and the road width are shown graphically for the individual steering concepts.

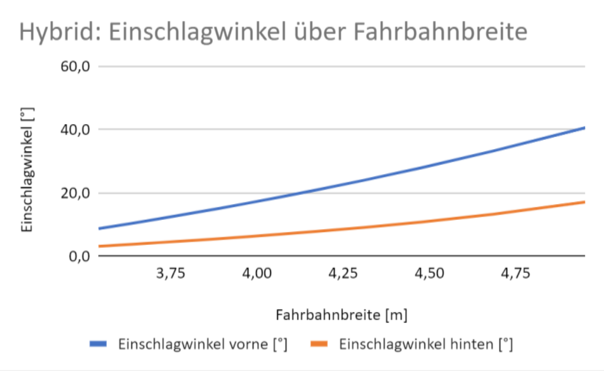












The carriageways on the Frankfurt bridges are designed from the outset with a view to maximum safety and the best possible comfort: For example, the dimensions of the towing curve of the largest vehicle were calculated and it was ensured that each curve could be navigated comfortably

For a large vehicle to be able to drive around a curve, it must not be too narrow or too tight. Therefore, the towing curves of the largest vehicles on the Frankfurt bridges were precisely determined using geometric relationships. Not only the wheelbase but also the front and rear overhangs are relevant here. The data shown are valid for the Neoplan NH 6/7 model, which has the largest vehicle dimensions.

Input parameters	Value	Unit
Length	8,39	m
Wheelbase	3,78	m
Front overhang	1,84	m
Rear overhang	2,77	m
Vehicle width	2,5	m
Front axle to rear axle steering ratio	0,7	m

Berechnungsergebnisse	Value	Unit
Curve inner radius of the rear wheel	5	m
Front axle steering angle	24	°
Angle of lock rear axle	9,1	°
Curve radius of the center of the curve	6,26	M
Turning circle diameter	15,19	m
Lane width	3,1	m

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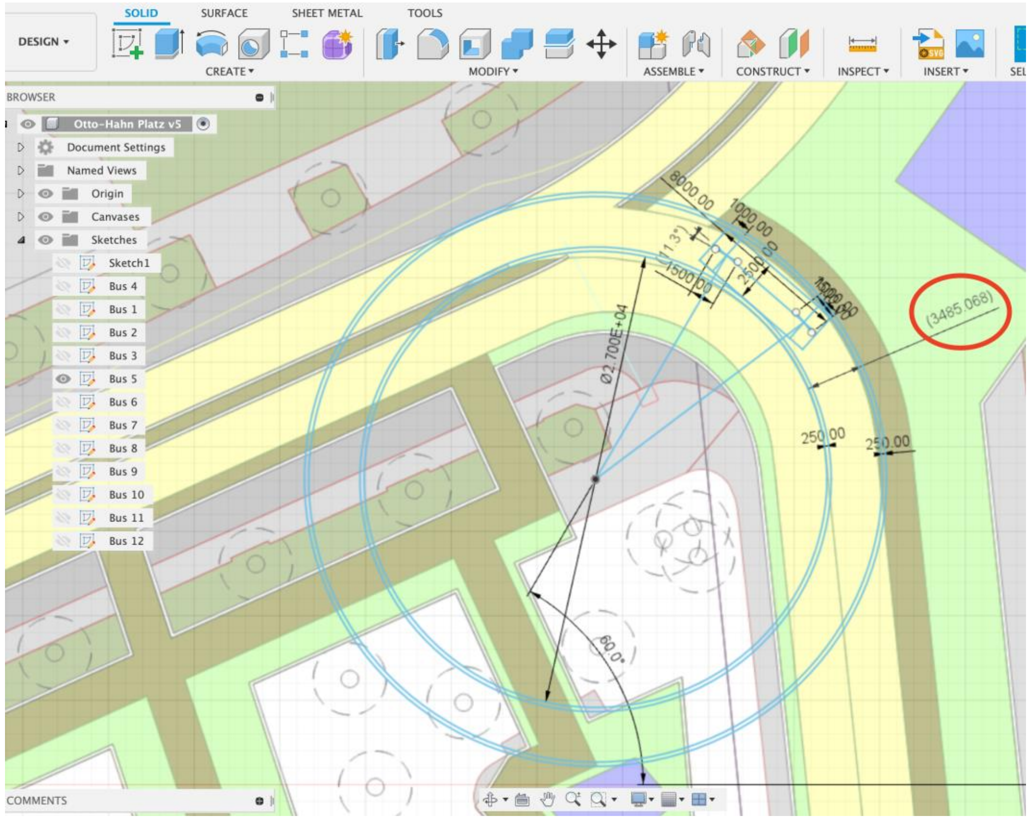
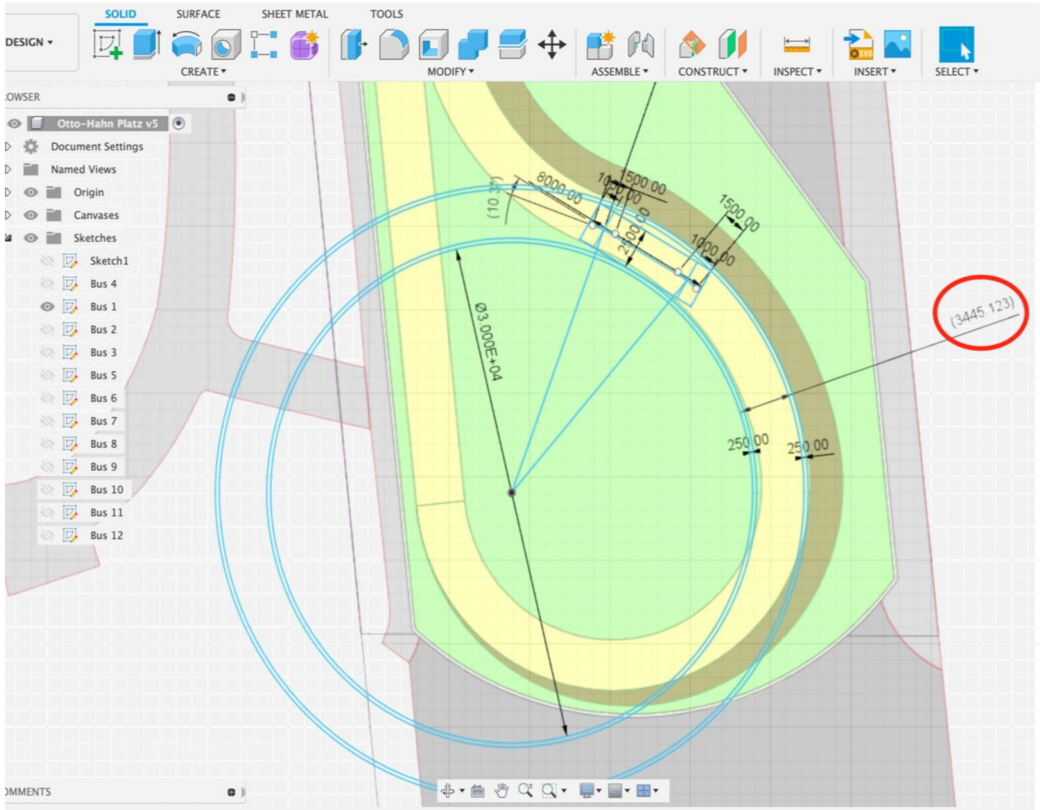
The route on the Frankfurt Bridges was planned according to the towing curves of the largest vehicles: Safety, driving comfort and smooth - i.e. time-saving - traffic are thus ensured

When planning the route, the radii and widths of the curves were created digitally and compared with the calculation results, ensuring that the route is suitable for all vehicles.





Conclusion: The highest level of comfort for autonomous driving will be possible on the bridges - as an attractive alternative to private transport.

Guardrails facing the sidewalks and automated pedestrian crosswalks keep the travel lanes on the bridges free of outside influences.

These protected, exclusive driving routes make it possible to solve the traditional problems of autonomous traffic systems: No vehicle is interfered with or brought to a halt by the arbitrary actions of humans or animals. In addition, all vehicles act exclusively under central computer control, which means that no road user can interfere and impair the optimized system.

High comfort, exceptional safety and speedy transport performance are the result.

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Vehicle Fleet: Modern Classic Cars

The vehicle fleet on the bridges: versatile and aesthetic

With a top speed of 30 km/h, the vehicles travel on the bridges in a fleet that could not be more diverse. From the outside, the vehicles have the look of vintage cars and futuristic vehicle models, but inside one will be surprised by the superior comfort. Ergonomic seats with enough legroom, power outlets, panoramic windows and other comforts increase the willingness of the population to one day do without their own car and instead use autonomously driving traffic in the city.

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Content: Vehicles are selected and designed for the bridge fleet to meet a wide variety of needs

Described is the use of vehicle designs from the past and the imaginative redesign of ultra-modern vehicle types.

Vintage cars by no means have to do without modern comfort. And futuristic vehicles, in turn, do not have to be cold and minimalist, but can be designed with a lot of warmth and creativity.

The decisive factor is that in a Car-Sharing fleet like the one on the bridges, the vehicle equipment is not uniform, but finely segmented to meet the needs of different passenger groups.

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Nostalgia and future in the form of vehicles

From nostalgic to futuristic - the vehicles of our bridge passenger transport are very different. The cars, buses and trains transport passengers back to the twenties, fifties, seventies of the last century or catapult them into the future; they are reminiscent of San Francisco, Porto or Rome, evoke a little holiday feeling in the middle of Frankfurt - and are above all fun.


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With the modern part of the fleet everything is conceivable

Since the vehicles on the Frankfurt bridges travel in "protected biotopes" and at low speeds, many more shapes and materials are conceivable for futuristic vehicles than for vehicles used in conventional road traffic: the latter have to meet higher requirements in terms of safety and aerodynamics, while there is much greater scope for creative design in the case of bridge vehicles.

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Classic cars are a piece of cultural heritage and also put you in a good mood

Bodies and many parts of buses and cars as well as wooden trains are handmade on the Frankfurt bridges in the "Master Academy for the Preservation and Innovation of European Craftsmanship".

Thus, not only beautiful cars and trains are created; also the craft of car body construction is preserved and further developed.

That being said, many people love classic cars and get excited when they come across a classic car on the road.

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The Bridge, Individual, traffic circles as a living transport museum on the second level in Frankfurt

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Circulating buses ensure the supply of the station within 1.5 min

In order to provide buses around the clock at the latest after 90 seconds at stations in the best case, buses stop in all route sections to serve this short-term demand. I.e. vehicles circulate in all route sections without stopping at stations.

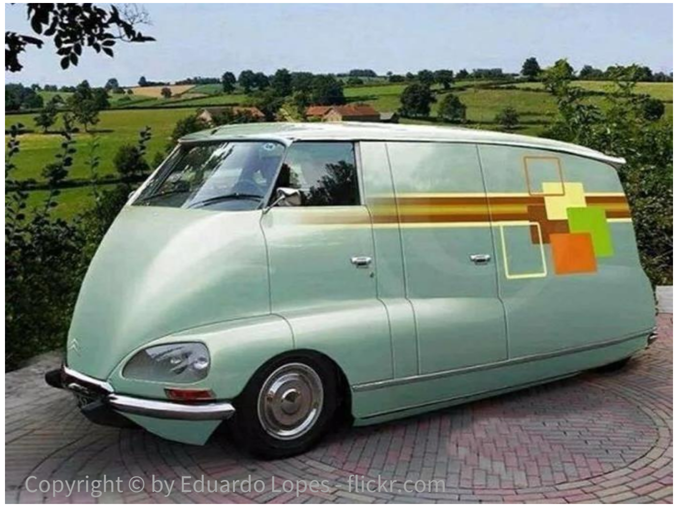
Carry out private journeys by car on demand

Due to the even distribution of the car parking bays over the route network, pick-up within 90 s is ensured even when a car journey is requested.

Special vehicles only drive when required / deployed

Statistics from the city of Frankfurt and other large German cities were used to determine how many police, fire brigade, refuse collection and post office trips there are on average on the bridges - this was taken into account in the simulation as background noise, i.e. randomly circling vehicles.

There are also suitable vintage models for special vehicles for postal delivery, refuse collection or for gardening teams.



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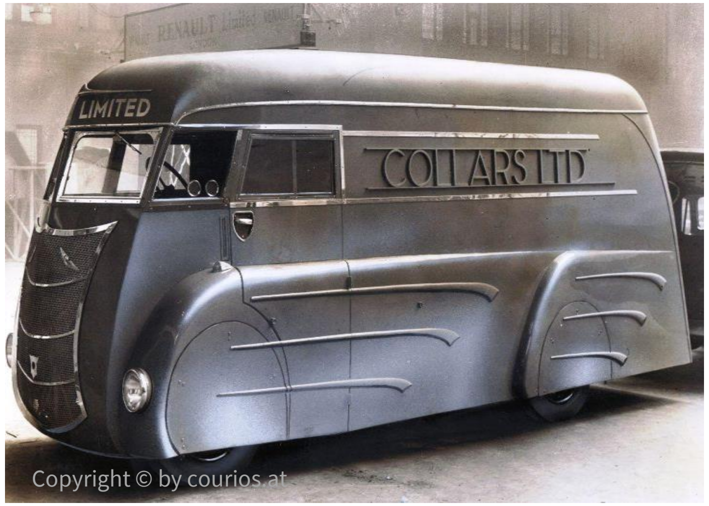


All vehicles are also equipped with the latest technical gadgets for the interior

Not only in the bodywork, but also in the interior, aesthetics, beauty and sometimes a little nostalgia are planned.

Depending on the vehicle model, the interior design looks different. In some cases, the design is based on historical models or a look into the future:

In one train, for example, the Wilhelminian era is revived with wood panelling and velvet upholstery, and the next vehicle whisks passengers away to a space shuttle - similar to the Panorama train in Switzerland.

But regardless of whether they have a retro look or are futuristic, all vehicles are equally equipped with power sockets, internet, air conditioning etc.

Plenty of space, comfort and technical equipment at a pleasant temperature

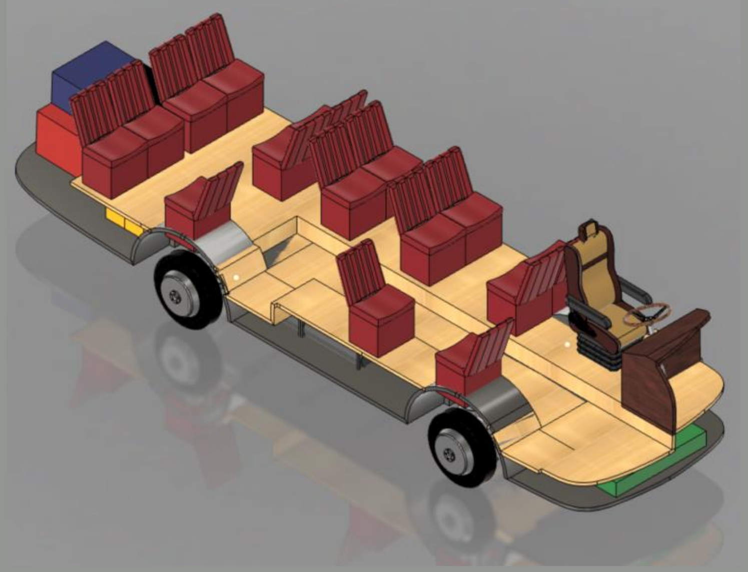
Regardless of what time the passengers board: The interior always offers the greatest possible comfort. The seats are ergonomically shaped, pleasantly upholstered and allow legroom.

All buses, trains and cars are also equipped with Internet, information screens and power outlets.

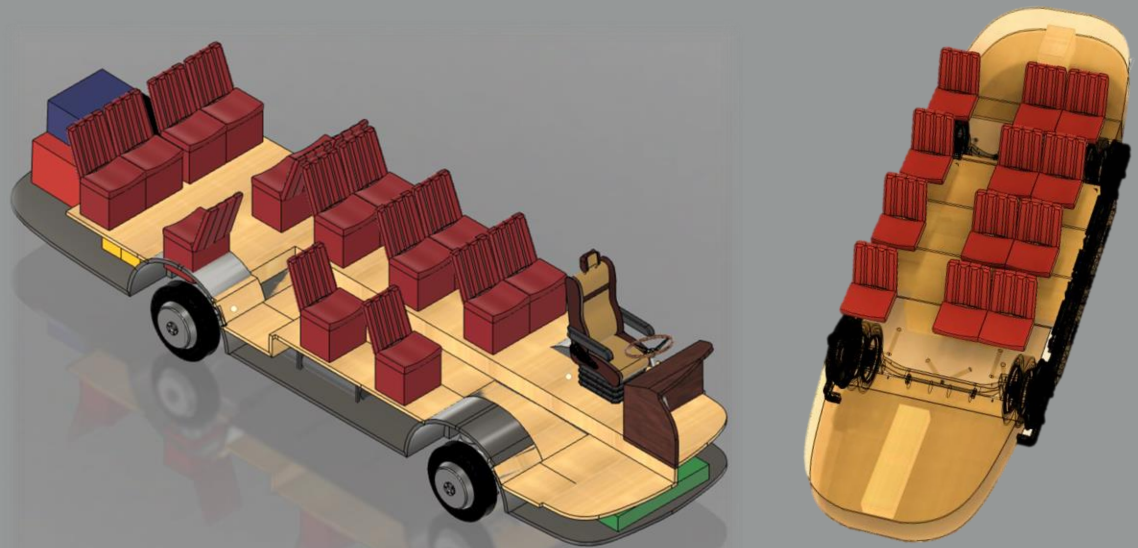
Seat heaters and air-conditioning systems ensure the right temperature in all vehicles - cool in summer, pleasantly warm in winter.We can draw on our experience with luxury interiors, such as those found in yachts or private jets, as all bridge vehicles are unique.

Trains and buses have varying seating arrangements and can be used by the central system in a targeted and suitable manner.

Seats facing each other
for families and groups of friends

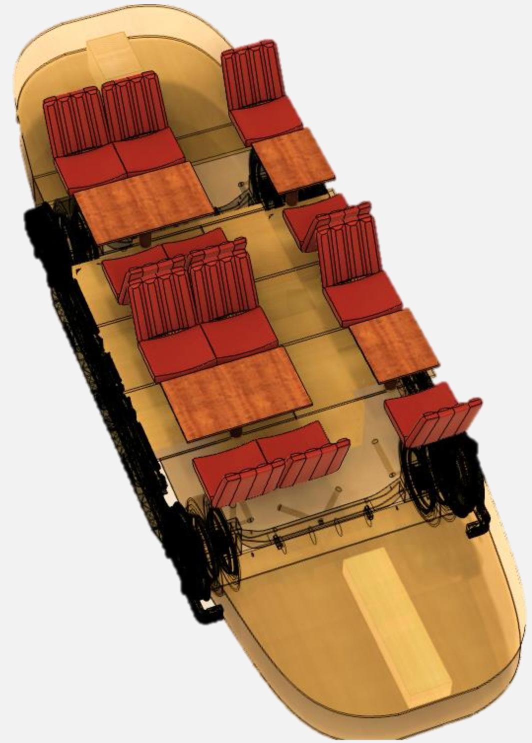


Seating arrangement ideal for working
on the way to school or to work



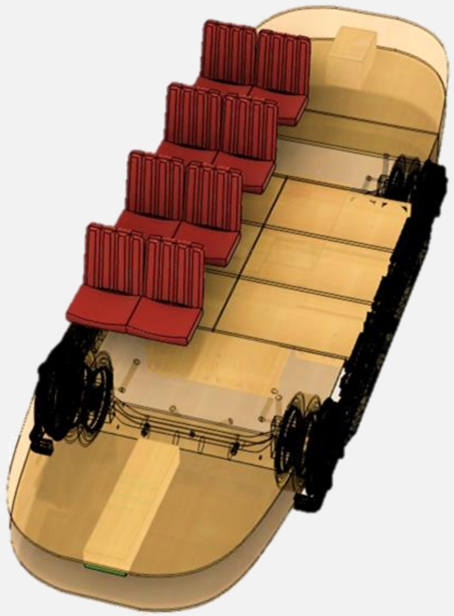
Other bridge vehicles have a lot of free space in the middle, for example to carry bicycles or luggage. Still others are suitable for tourists or for excursions of citizens, with larger tables between the seats for eating and drinking.

There are also particularly suitable vehicles for leisure-oriented journeys or journeys with luggage and other bulky items.



Some vehicles - especially trams - have a seating arrangement with a table in the middle: they are particularly suitable, for example, for eating and drinking with children while looking out of the window, or for excursionists who simply want to enjoy the view.

There are also vehicles that have fewer seats, but plenty of free space next to the seats: This can be used for bicycles, prams, luggage or large shopping bags.



The vehicles that offer a lot of space next to the seats - just like the barrier-free vehicles with a lot of space in the middle - are also sent preferentially to the bridge cycle paths by the guidance system: These come from the outer arms in the west and east almost as far as the ring road - until the development next to the bridge gets too close to the edge of the bridge. There, the bridge bike lanes end, and the cyclists can either ride down to the street with bike elevators and continue from there, or they call a bridge vehicle with enough space and have themselves and their bike transported to the city center before they then switch to the street there.

A database specifies which classic cars are allowed to drive on the Frankfurt bridges - they must not be too long or too wide.

VW Bus Samba T1 -1966
Length/Width/Height
430/180/192 cm

Tempo Vidal Matador 1951
Length/Width/Height
525/186/220 cm

Bogward B 1500 D - 1953
Length/Width/Height
540/200/250 cm

Cheese drill Setra - 1964
Length/Width/Height
670/220/280 cm

Mindener K&F GmbH 1959
Length/Width/Height
725/218/257 cm

Steyr 1955
Length/Width/Height
746/220/240 cm

The classic cars on Frankfurt's bridges should be designed as closely as possible to the original from the outside.

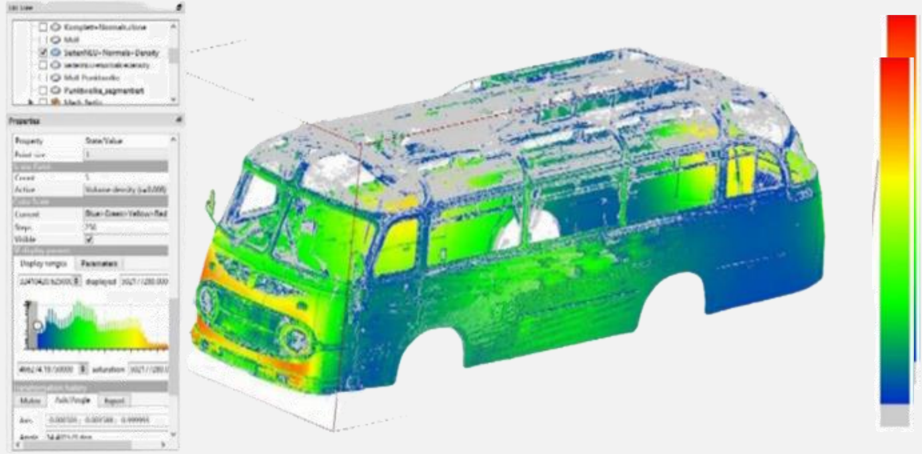
Every classic car has its own unique shape. In order to be able to create the modern version of a classic car for the Frankfurt Bridges concept as close as possible to the original, a classic car body was scanned.

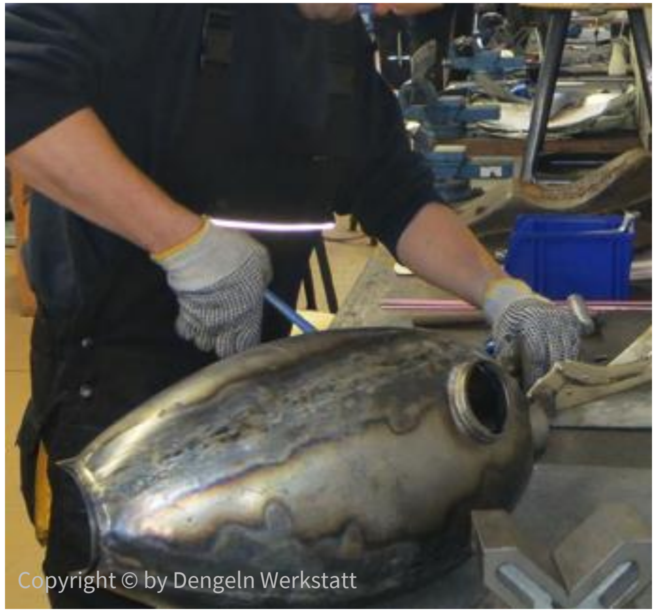
For this purpose, a well-preserved and restored vehicle was digitized with the help of laser scanners and cameras. In the next step, the vehicle was remodeled on the computer and adapted to the requirements of the Frankfurt bridges. The vehicle shown is the bus of the type "NH 6/7" from the company "Neoplan".

The vintage bus "Neoplan NH 6/7" was remodeled with the help of a 3D scan

The lasers and cameras create points that "float" three-dimensionally in space. At each position where a physical component of the vehicle is located, such a point is automatically placed. The collection of all points is called a point cloud.

In the next step, points that had been set incorrectly were eliminated. The vehicle was then remodeled on the computer based on these points and adapted to the requirements of the Frankfurt bridges.





The vehicles on the Frankfurt bridges: beauty produced by the Master Academy

The bodies of the buses and cars are to be manufactured in the master craftsmen's academy on the Frankfurt bridges, just like the wagons of the trains. The only question is: Can anyone still do it?

Well, it's not called the "Master Academy for the Preservation and Innovation of European Craftsmanship" for nothing: Because even if almost all skills are slowly but surely dying out - if not in Germany, then usually somewhere in Europe you can *still* find workshops that can dengel the bodywork for a vintage car, make an old tram out of wood or even bend the frame of a bus. With the support of the vehicle companies that have the design rights and possibly also helpful planning documents for their old gems of yesteryear, unique productions should be possible.

Conclusion: The beautiful vehicles of the bridge fleet generate high acceptance for autonomously driving Car-Sharing

On Frankfurt's bridges, vintage and futuristic vehicles offer a positive driving experience for all segments of the population: Families, professionals, students or even people who need barrier-free vehicles - there are appropriate transport options with suitable equipment for everyone.

In addition, passengers as well as passers-by and residents have a living transport museum before their eyes, which can also be experienced directly. Driving the bridge vehicles is an enriching experience for all classic car fans, as the bodies and equipment of the replicas are true to the original and handcrafted by the Master Academy for the Preservation and Innovation of European Craftsmanship.

The combination of traditional craftsmanship with ultra-modern technology, environmentally friendly sustainability and luxurious "comfort for all" is unique in the world - and it's no coincidence that it takes place in the car country of Germany!

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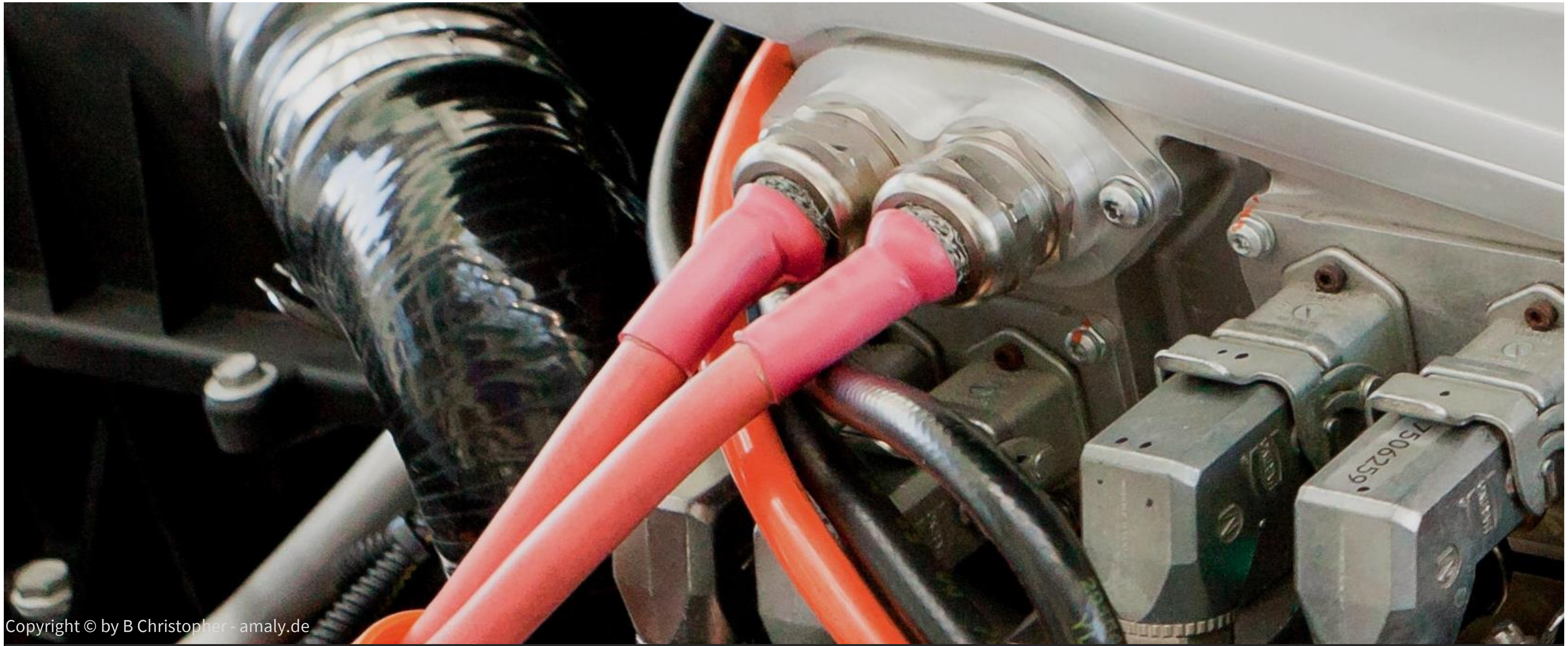

CO2 emissions, material and energy consumption are reduced on the bridges through the use of hydrogen and e-vehicles, lightweight construction and intelligent controls

The innovative forms of drive in combination with autonomous driving on a specially designed route open up new possibilities for making a vehicle particularly sustainable. With a planned durability of 100 years, a significant proportion of CO2 emissions and material can be saved in both production and operation. In addition, the central intelligent control of the vehicles results in a significant reduction in energy consumption.

Content: The bridge fleet is particularly environmentally friendly because the most sustainable solution is always chosen for the propulsion system, the selection of building materials and the frame construction.

There are battery-electric and hydrogen-electric vehicles on the bridges. The required refuelling infrastructure is not only provided by the bridges for their own vehicles; rather, e-cars can also charge their batteries down on the roads, and hydrogen vehicles can fill their tanks at the hydrogen filling stations located on the seven outer arms of the bridges as well as on the bridge ring.

The second major lever for the sustainability of the fleet is to save material through structural optimisation, a significantly lower number of vehicles and the long life cycles of the vehicles.

Furthermore, in the selection of materials, emphasis is placed on sustainable building materials or, where possible, on renewable raw materials.

Both hydrogen tanks and batteries are used in the vehicles on the Frankfurt bridges

When it comes to climate-friendly drives, battery-electric and hydrogen-electric drives are always at odds with each other.

Both are planned for the Frankfurt bridges, because it can be assumed that, depending on the geographical location and the respective transport task, sometimes one technology and sometimes the other is more environmentally friendly and therefore "better" in terms of the overall ecological footprint.

Since the German automotive industry still wants to play a decisive role, not only in Germany but also with exports worldwide, it is logical that in a German "showcase of innovations" such as the Frankfurt bridges, both technologies are planned as promising drive systems for the future.

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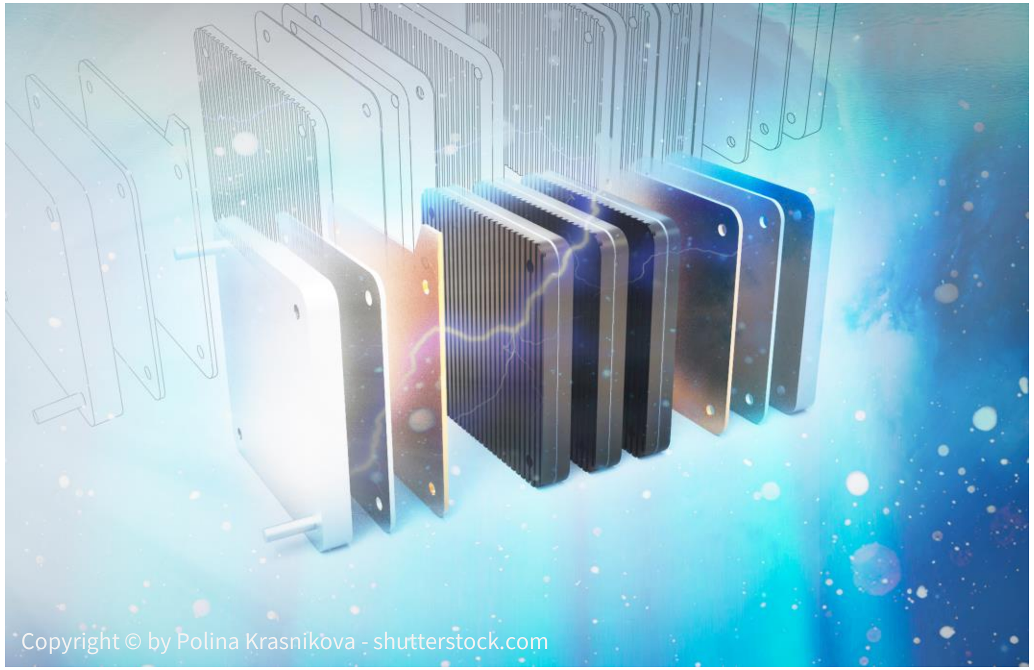
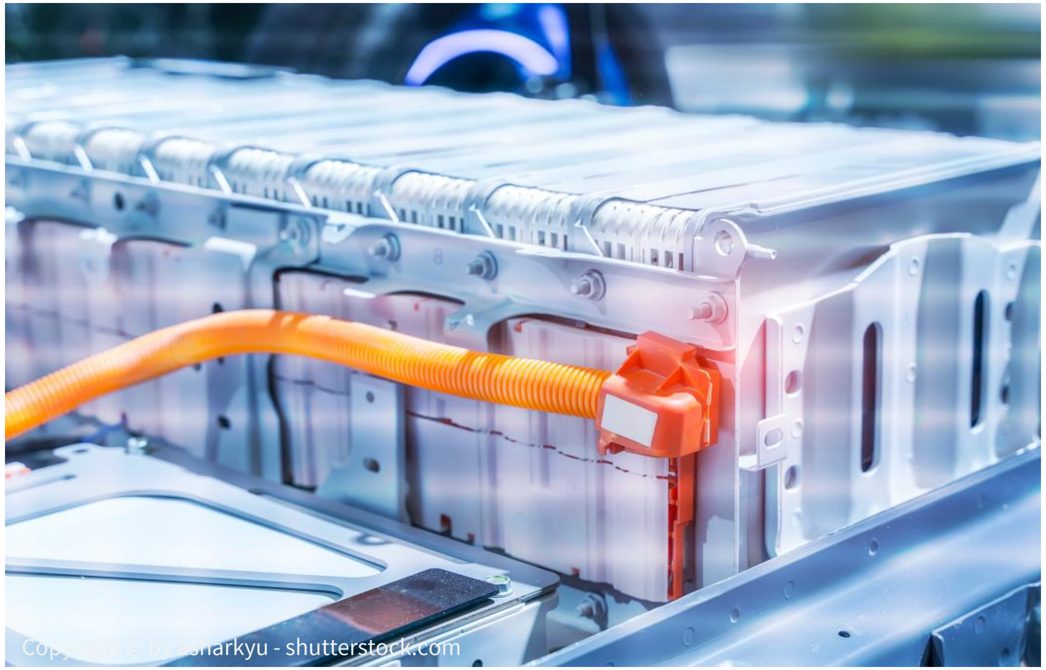




The difference between hydrogen and battery vehicles

First of all: Both types of vehicle are electrically powered. Electric current is therefore always required for locomotion.

The difference: electric cars have a battery that provides the electricity. In hydrogen cars, hydrogen is converted into electricity by a fuel cell. The hydrogen car only has a small battery to store energy temporarily.

Since there will be a lot of green energy on the bridges, it makes sense to run part of the fleet on hydrogen electricity

The production of batteries requires special raw materials, in particular lithium, cobalt and nickel, whose mining conditions and other factors are particularly critical. Hydrogen, on the other hand, can be produced by electrolysers and then stored in tanks, the production of which does not require comparable raw materials for manufacture. Moreover, energy in the form of hydrogen can be stored for longer periods without major losses, whereas storage in correspondingly large batteries is only possible for days or a few weeks.

With the help of the Frankfurt bridges, a surplus of electrical energy is produced, which is stored both for short-term use in redox or lithium batteries and for the longer term in tanks in the form of hydrogen.

The energy surpluses of the bridges will be made available to the citizens of Frankfurt for their e-cars and hydrogen vehicles.

Covering the needs of vehicles on the bridges	Quantity	Power consumption(kWh/a)	Electricity demand (GW)
Vehicles with electricity on the bridges	200	12.000	16
Vehicles with H2 on the bridges	100	179.000	21
Meeting the needs of vehicles next to the bridges	**Quantity**	**Power consumption(kWh/a)**	**Electricity demand (GW)**
Buses with H2 next to the bridges	100	150.000	15
Vehicles with H2 next to the bridges	50	82.000	4
Vehicles with electricity next to the bridge (300 days)	6.000	24.500	147
Vehicles with electricity next to the bridges (365 nights)	1.500	27.000	41

Vehicles can be refuelled not only on the bridges, but also under them

The hydrogen filling stations on the bridges were designed in such a way that all hydrogen-powered vehicles for bridge traffic can be automatically refuelled with them. This means that the autonomous vehicles automatically drive into the hydrogen filling station and remain there until the refuelling process is complete.

But it is not only the bridge vehicles that will be connected; the bridges will also provide Frankfurt's citizens with seven filling stations at various locations in Frankfurt.

The citizens of Frankfurt can fill up their electric cars with green electricity at the bridge's own electric filling stations.

Frankfurt's bridges provide plenty of green energy, as many surfaces are equipped with photovoltaic panels.

This energy is not only used to power the houses and shops on the bridges, but also to power the battery electric vehicles.

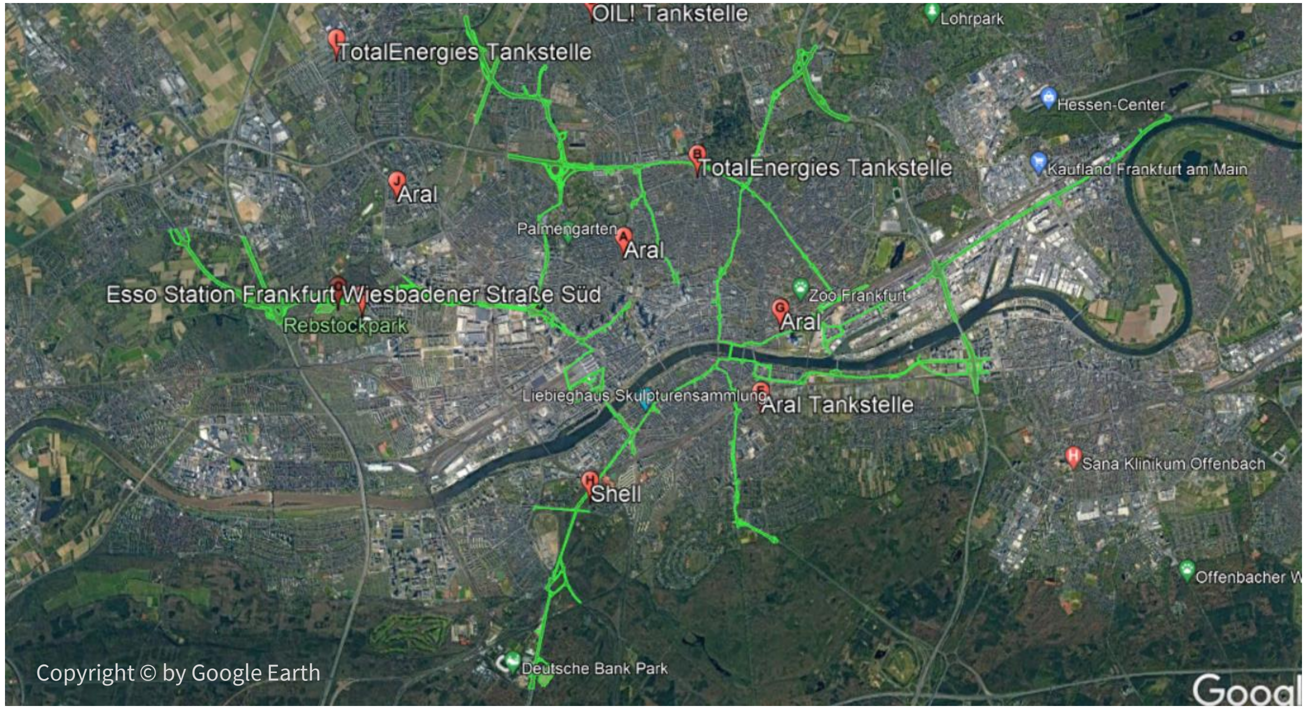
In addition, residents can also use the charging points at the pillars of the bridges to charge their electric vehicles.

There are bridge charging stations, but more remote charging stations in the city are also supplied with electricity from photovoltaic surpluses.

Surplus electricity from bridge solar modules and the photovoltaics of the energy belts around Frankfurt will be stored in the form of hydrogen and made available to both the bridge fleet and Frankfurt's H2 filling stations.

There are 100 hydrogen-electric vehicles on Frankfurt's bridges that can be powered using the bridges' energy infrastructure. However, such a high surplus of green hydrogen is produced that around 80 Frankfurt buses operated by the Frankfurt transport company can also be supplied - this corresponds to 20 percent of Frankfurt's bus routes.

In addition, there is the energy surplus from the (bridge-independent) energy belts along the motorways and federal roads around Frankfurt, which also feed their surplus electricity to the electrolysers of the hydrogen filling stations in the extended urban area.



Frankfurt hydrogen filling stations will probably be located at the major exit roads, because the most important clientele will be heavy goods vehicles.

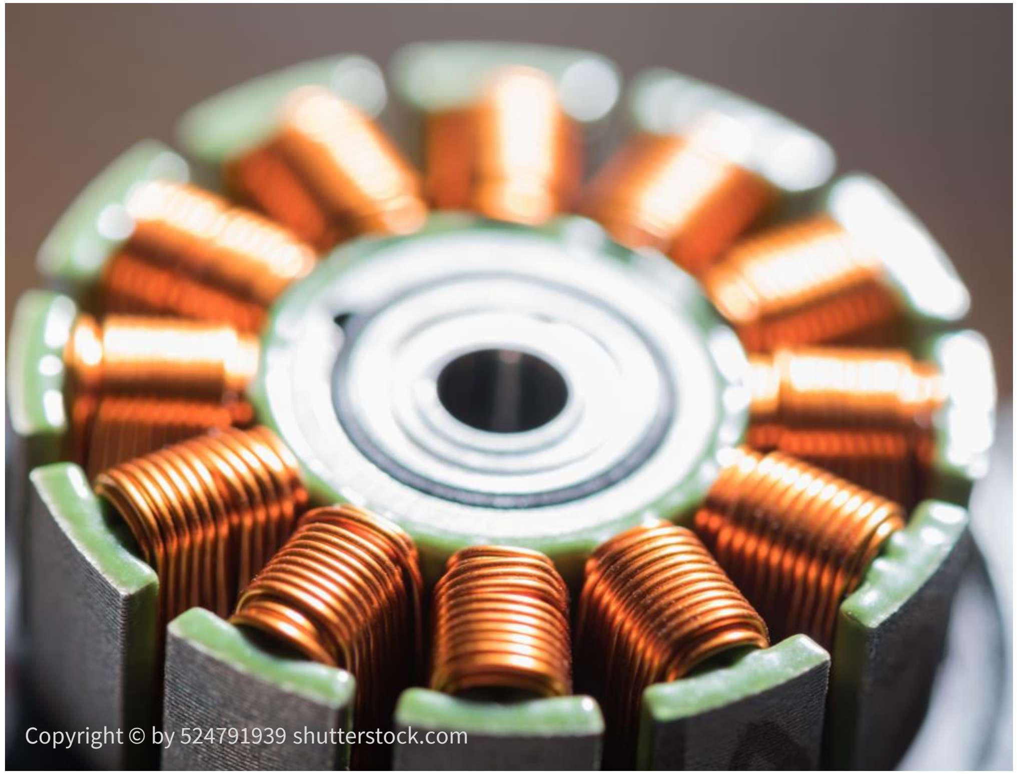
As no other services are expected to be offered apart from refuelling and the H2 tanks, like the electrolysers, will be installed underground, i.e. in a very space-saving manner, the proximity to the current existing filling stations is an advantage.

Anticipatory driving is not only pleasant, but also saves energy

The central organization ensures that vehicles run smoothly and generally only stop when necessary. In addition, they do not have to brake and restart pointlessly, which consumes the most energy in urban traffic.

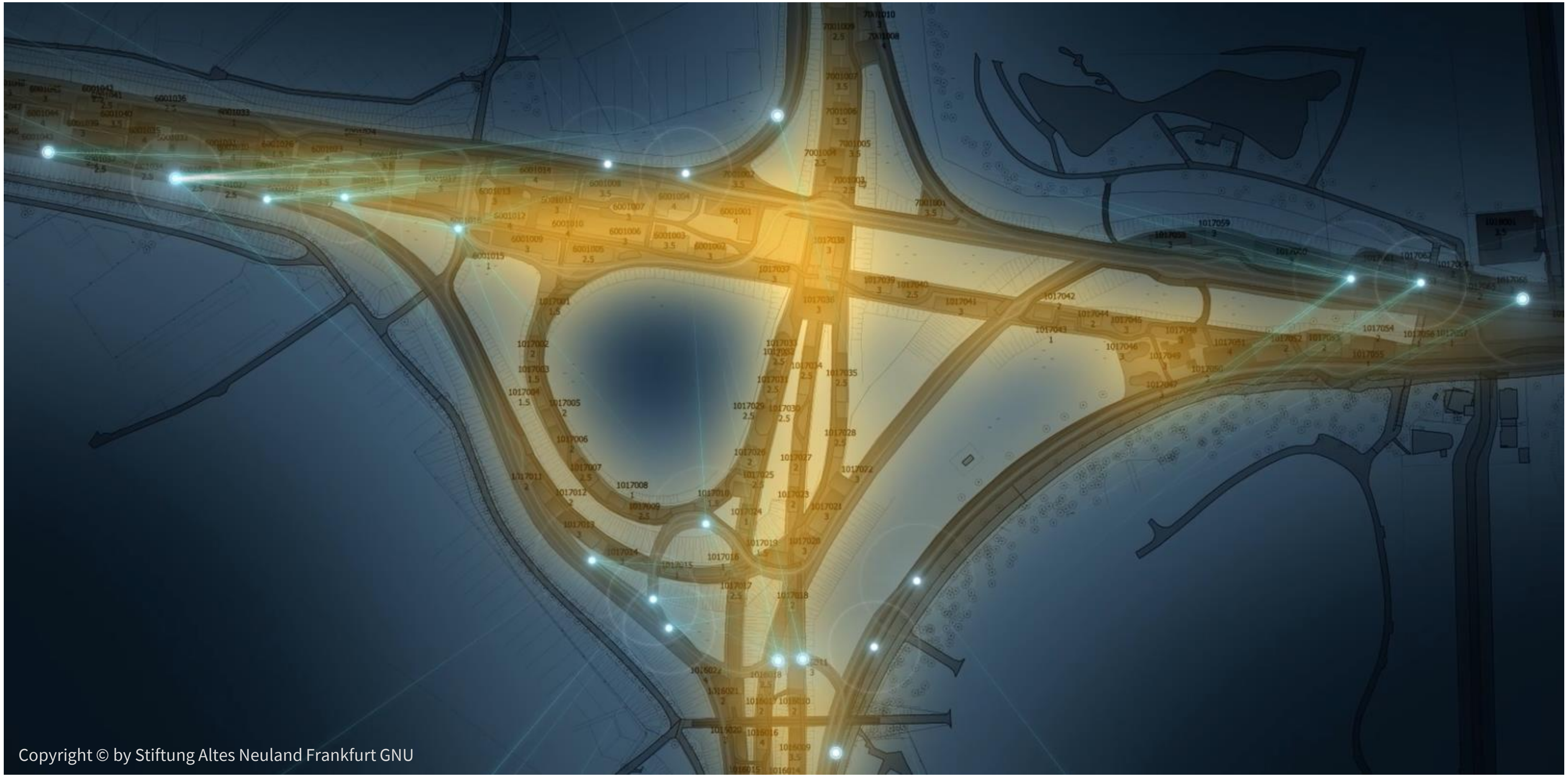
Vehicles on Frankfurt bridges brake less frequently, and when they do, they do so with recuperation.

In electric driving, energy is fed back into the battery by the engine during braking: This so-called recuperation is already used in today's vehicles and significantly increases energy efficiency.



The centrally controlled vehicles on the Frankfurt bridges offer significantly reduced CO_2 emissions through demand-oriented route planning

No journeys "for free": no detours, no empty journeys, not one vehicle too large for just a few or one passenger - this too is only possible with central organisation of transport



A centrally optimised system with vehicles in the Car-Sharing model requires fewer vehicles and resources, which saves energy

Intelligent, demand-oriented fleet planning means that fewer vehicles are needed, as individual vehicles do not have to be kept on hand for each person.

A car is stationary for up to 90% of its lifetime, i.e. it is only used for 10% of its time (if a study by the Institute of Social and Economic Research at the University of Cologne is to be believed, a car is actually only used for 5% of its time).

With autonomous driving on bridges, many people are transported by the same vehicles, both buses and trains, and cars. So you don't have to own the vehicles for comfortable usability, but can call them as needed via app.

Since this system is attractively priced, it is expected that more and more people in the city will no longer see a need for their own car. This reduces the demand for cars in general - and thus also the demand for lithium batteries and other materials. To achieve this goal, particular attention was paid to the cleanliness of the vehicles and ease of booking.

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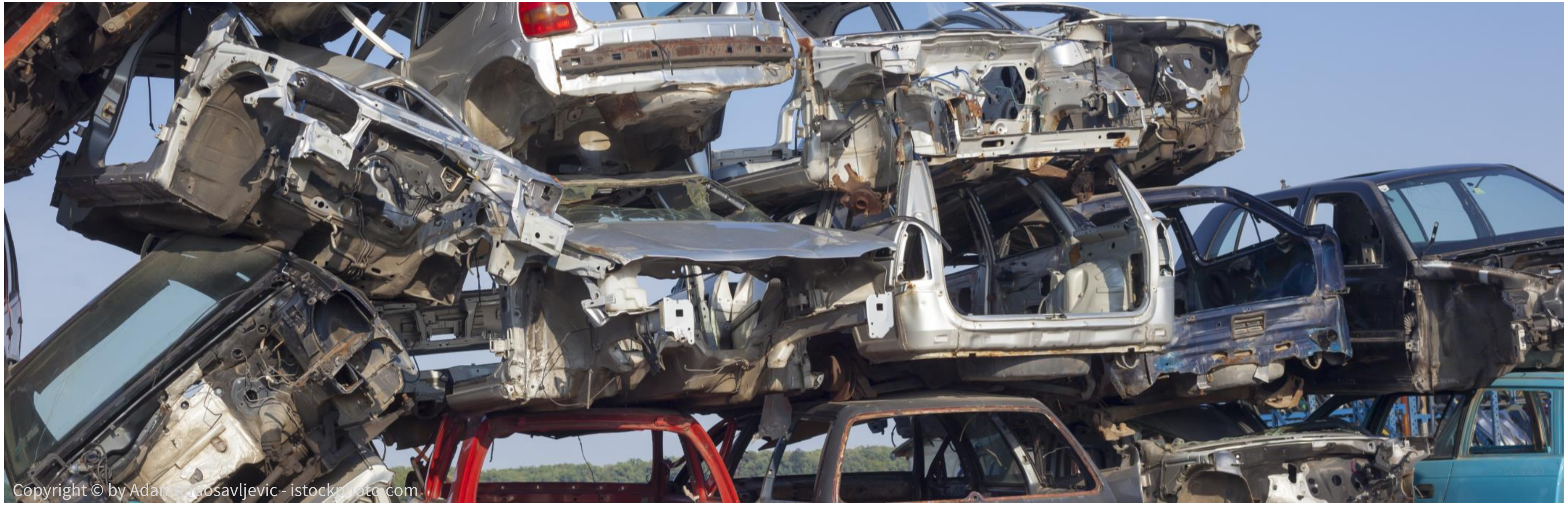
Sustainability means fewer car replacement cycles on Frankfurt bridges due to appreciation

Vehicles are valued through craftsmanship and attention to detail

Car bodies are to be partially handcrafted in the master academy. Decorative elements and the attention to detail typical of classic cars are intended to showcase the beauty of the vehicles again and again. The aim is to get away from the throwaway culture and back to an appreciation of things. This significantly saves material and energy.

Fewer accidents mean that vehicles only need to be replaced very rarely

The central control and the autonomous driving mode prevent accidents very reliably. Vehicles cannot usually be destroyed by accidents or carelessness, as the autonomous system controls reliably and correctly at all times. Overconfidence and negligence can be ruled out. The vehicles on the bridges can be designed accordingly elaborately.



Due to the longevity of the vehicles on the bridges, there is no need to constantly buy new cars, buses and trains - against the background of increasingly scarce resources, this is an important factor in the city of the future.

For the vehicles on Frankfurt's bridges, a service life of one hundred or more years is the target. The fact that an astonishing longevity is also possible for regularly used vehicles is still demonstrated today by roadworthy cars from the fifties, sixties or seventies, as seen for example in countries such as Cuba or Morocco.

The longevity of the vehicles must be ensured by regular maintenance and care as well as, quite classically, by rapid repairs when necessary: Through "predictive maintenance", the vehicles know when it is time for a check-up or repair and drive to the workshop. There they are checked, parts are repaired shortly before they become defective or - if this is not possible - replaced. The modular design of the vehicles makes it possible to replace individual parts. This means that an entire complex does not have to be replaced - as is so often the case today - even though only a single element is defective.

When selecting the materials for the vehicles on the bridges, environmental compatibility - from extraction to disposal - was taken into account.

The materials from which the vehicles are made are consistently designed with environmental compatibility in mind - both in extraction and processing as well as in disposal - even if this is only to take place in 100 years or more. The aim is to consider the complete life cycle of all materials, i.e. from extraction to disposal and possible reuse. If you look at old wooden tracks, it is impressive how long they serve.

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Wherever possible, renewable and recyclable materials are used for the vehicles on the bridges.

Wherever possible, renewable raw materials are used, such as wood in the construction of the tracks, or hemp, flax and other natural fibres in the interior panelling and fittings.

Popcorn, for example, can be used for insulation. Many different sustainable input materials can be tried out on the Frankfurt bridges.

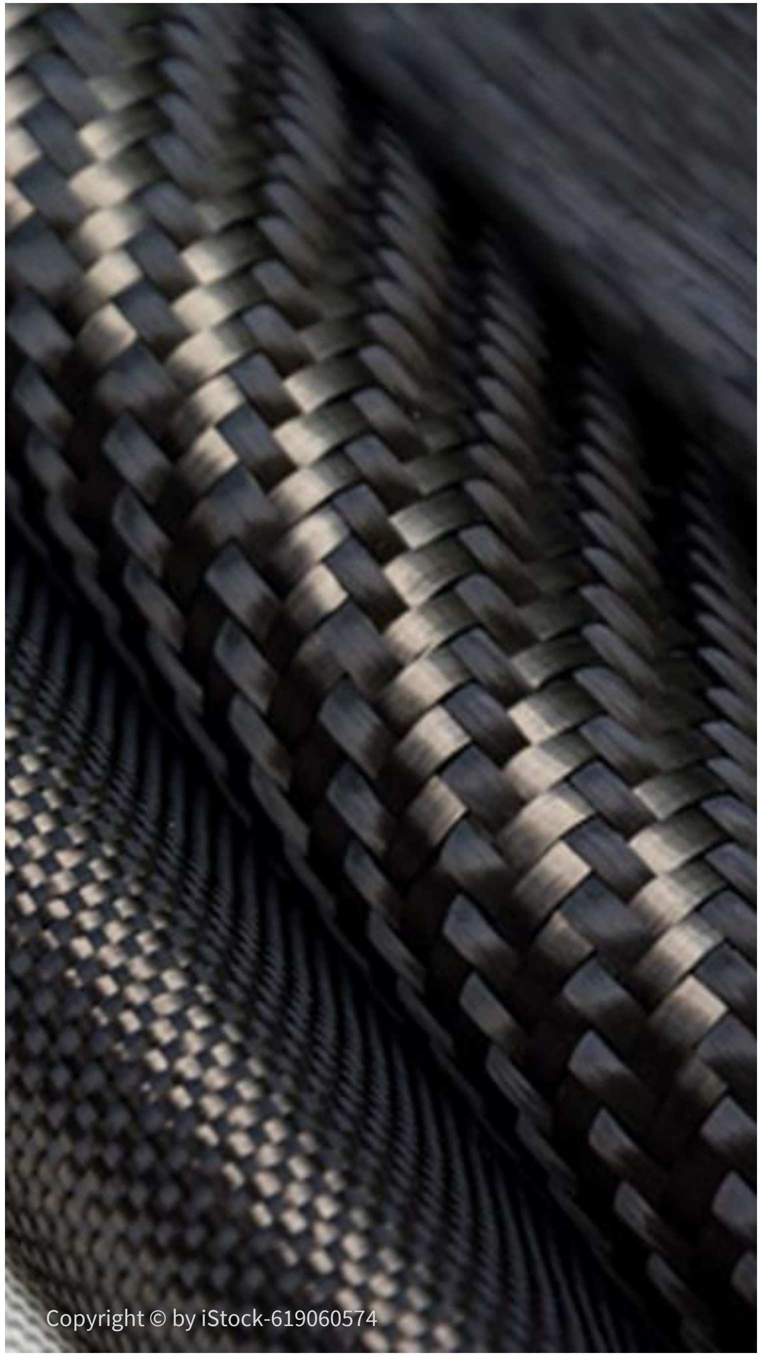
As far as possible, at the end of their useful life, all materials should either be returned to the raw material cycle or be able to be reused by up-, down- or recycling.

Extremely durable materials have the advantage of longer life cycles, but the disadvantage that they are not recyclable or degradable without leaving residues.

Fibre composites, which are problematic in terms of their recyclability, are largely dispensed with in the construction of vehicle bodies on the Frankfurt bridges:

In fibre composites, glass or carbon fibres are woven into a carrier material and then bonded with resin. This makes the material high-strength and durable. However, the two components can no longer be separated from each other.

Unfortunately, it does not make sense to completely dispense with fiber composites. For example, the hydrogen tanks are made of fibre composite material. Their poor recyclability is compensated for by the long service life of the vehicles.

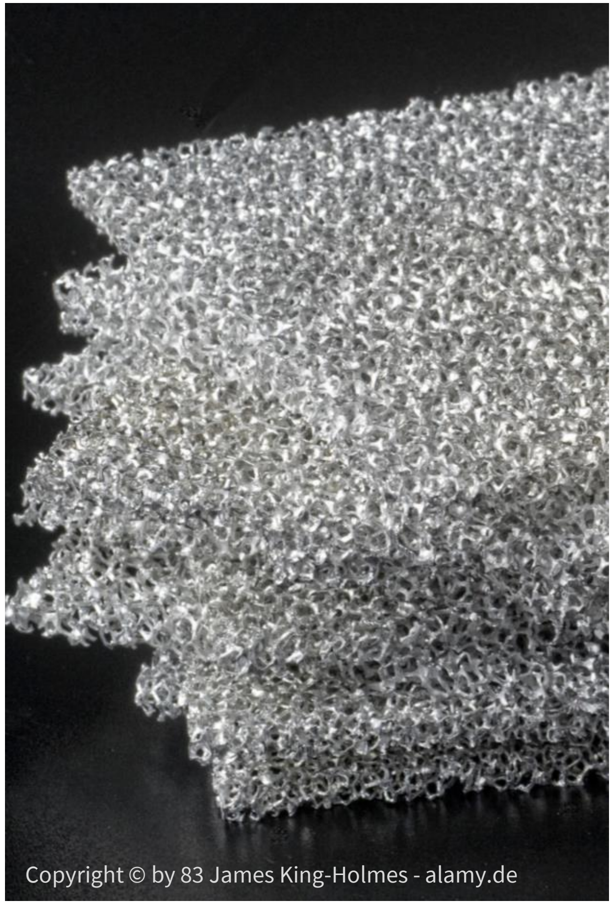


Vehicles on the bridges are of lightweight construction

The most important framework condition for the vehicles on the bridges: they have to be light! There are several reasons for this. On the one hand, lighter vehicles can save materials in bridge construction, because they are not subjected to so much additional stress by the vehicles. On the other hand, the heavy crash structure in the vehicle body can be dispensed with due to the autonomous system and the "biotope environment".

To achieve this goal, all "masses", i.e. weights of the individual vehicle parts, were compiled in a "mass balance". In the next step, each component was checked to see whether and how it could be made lighter than before.

While the oldtimers still drove with the heavy combustion engine and had heavy steel bodies, today there is fuel cell technology as an alternative and a wide range of lightweight materials for the construction of the body.



Over the past decades, cars have become heavier and heavier on average - only in recent years has lightweight construction come into focus

Yet one has caused the other: Anyone who drives faster is exposed to greater force in the event of an accident. In order to protect the occupants, the manufacturers strengthened the bodies and packed numerous safety equipment into the cars.

The result: the cars became even heavier. This led to both material and energy waste: On the one hand, the production of raw materials for car manufacturing increases, and on the other hand, a heavier vehicle requires more energy to accelerate.

Since the vehicles on the Frankfurt bridges are manufactured in lightweight construction, a lot of drive energy is saved

Whether buses, trains or passenger cars - the entire vehicle fleet is manufactured in lightweight construction, which is made possible by the significantly reduced risk of accidents and reduced impact force. This is because all vehicles are networked via a central control system, through which information about the positions, speeds and next manoeuvres of all vehicles is constantly exchanged, thus preventing accidents. In addition, the vehicles do not travel faster than 30 kilometers per hour, so that the reinforcements of the bodywork that are customary today are also unnecessary to a large extent.

And with every gram less, drive energy is also saved: the vehicles on the Frankfurt bridges weigh around 20 to 40 percent less than conventional cars. This results in around 10 percent lower energy consumption.
A lightweight model has been developed for the longest bus and the longest train on the bridges as an example (more ->....)

The German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt; DLR) has already developed a number of lightweight body structures - e.g. this multi-material body structure with a high proportion of fibre-reinforced plastics

In order to be able to implement lightweight construction, the component weights of the "Neoplan NH 6/7" vehicle were documented in a mass balance.

Category	Value	Unit
Frame, bodywork and chassis		
Of which General	2.158	Kg
Thereof frame	1.783	Kg
Thereof axles	1.275	Kg
Autonomous system, climate, light elements	363	Kg
Drive train	860	Kg
Unladen weight vehicle	**6.439**	**Kg**
Passengers	1.810	Kg
Total weight in kg	**8.249**	**Kg**

The weights of the main vehicle components were entered in a mass balance table. This allows a relatively accurate weight estimate of the vehicles to be made.

For a better overview, the weights are divided into different categories: "Frame, bodywork and chassis", "Autonomous system, climate, light elements", "Powertrain" and "Passengers".

For each category there are extensive individual lists with the respective components and weights.

Savings potentials: Optimization of the frame structure, FEM analysis of the axle beams

Frame	Value	Unit
Upper frame	1064	Kg
Lower frame	719	Kg

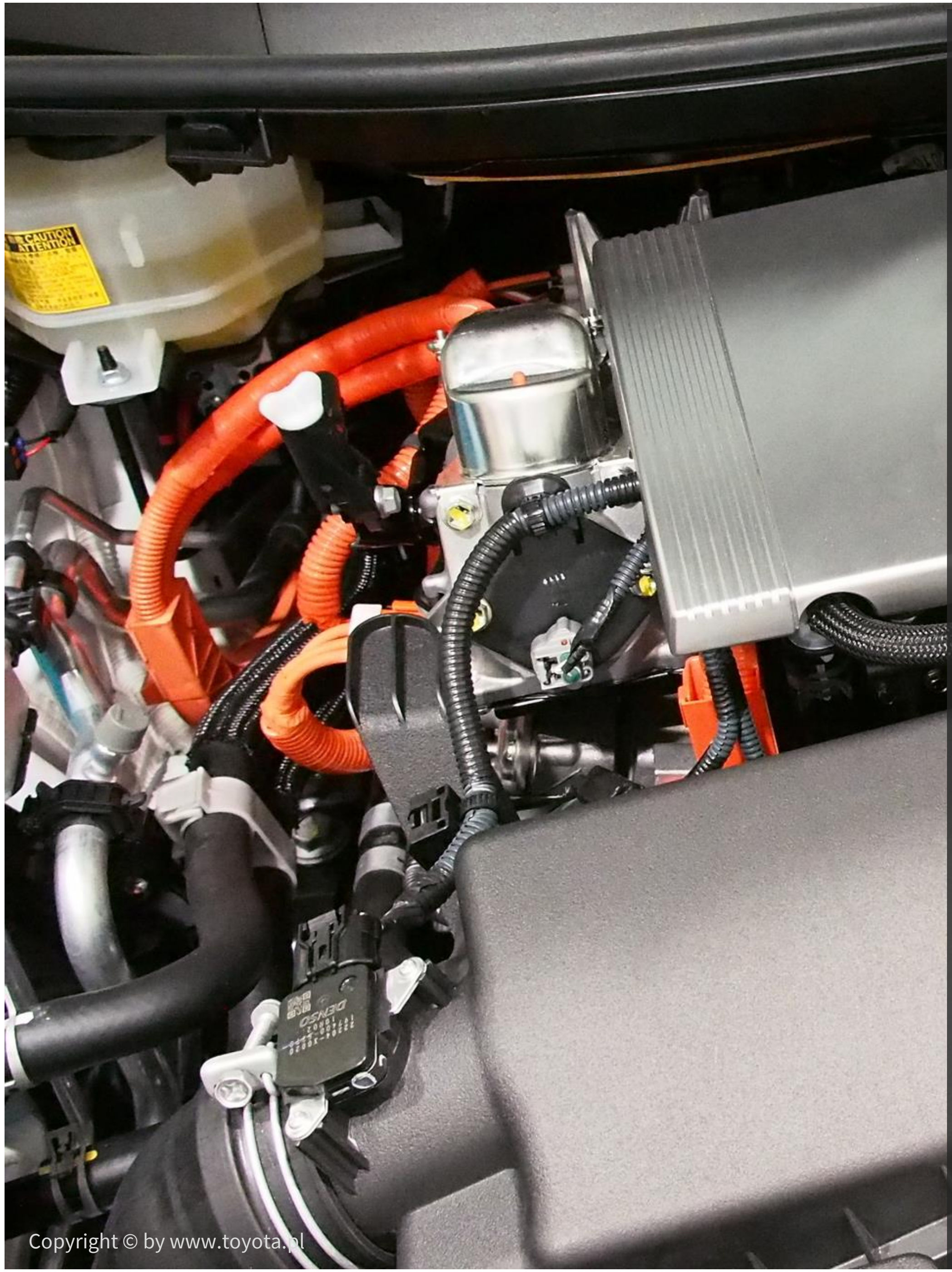
Interior	Value	Unit
Seats	285	Kg
Driver's seat	60	Kg
Interior planking	644	Kg
Air pipes, heating pipes, outlets, human operator interface	150	Kg
Infotainment system & sensor technology	180	Kg

Exterior: Planking outside	Value	Unit
Side glazing	123	Kg
Windscreen	30	Kg
Rear window	43	Kg
Panoramic roof	185	Kg

An extract from the mass balance shows the individual weights of components

The weights of the areas "Frame", "Interior" and "Exterior: Planking outside" are shown in simplified form as an extract from the original mass balance file.

The most important weight components of these ranges can be taken from the list.



Conclusion: Optimizing the vehicle fleet for sustainability serves as a model for the vehicle world of the future

Due to the "track biotope" that can be realized on the bridges, the bridge vehicles are exposed to significantly reduced loads: The driving speed is low, the crash risk is close to zero, and the risk of tipping over is also virtually non-existent - all factors that favor a sustainable choice of materials and low material consumption (and thus low weight).

Even though it will probably be decades before comparable traffic can be realized on the roads, the right characteristics for the vehicle world of the future can be developed and applied here in advance.

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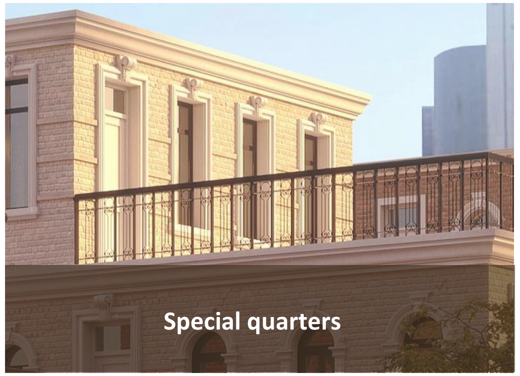
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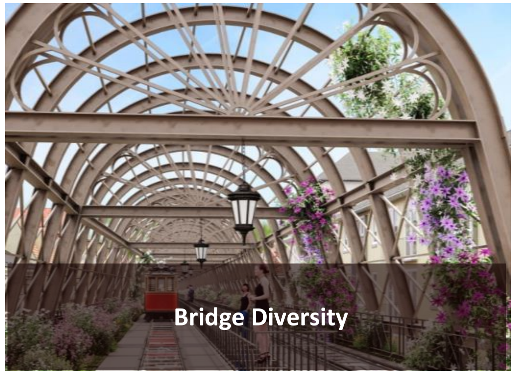
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The feasibility of the bridge-vehicle concept was checked with some development steps

The example of a bus was used to show how the most important components of a vehicle should be put together in a modular way so that the widest possible range of different vehicles can be designed with the same "biotopic" framework conditions without having to develop each vehicle individually. Some components, such as the vehicle frame or the wheel assembly, were analysed in detail, while standard solutions were used for others. The development of the bridge fleet is thus in line with the current trend in the automotive industry: different existing models are no longer incrementally optimized, but the vehicles are "rethought".

Content: Three aspects of vehicle development were examined in more detail - FEM, modularity and design or powertrain simulation.

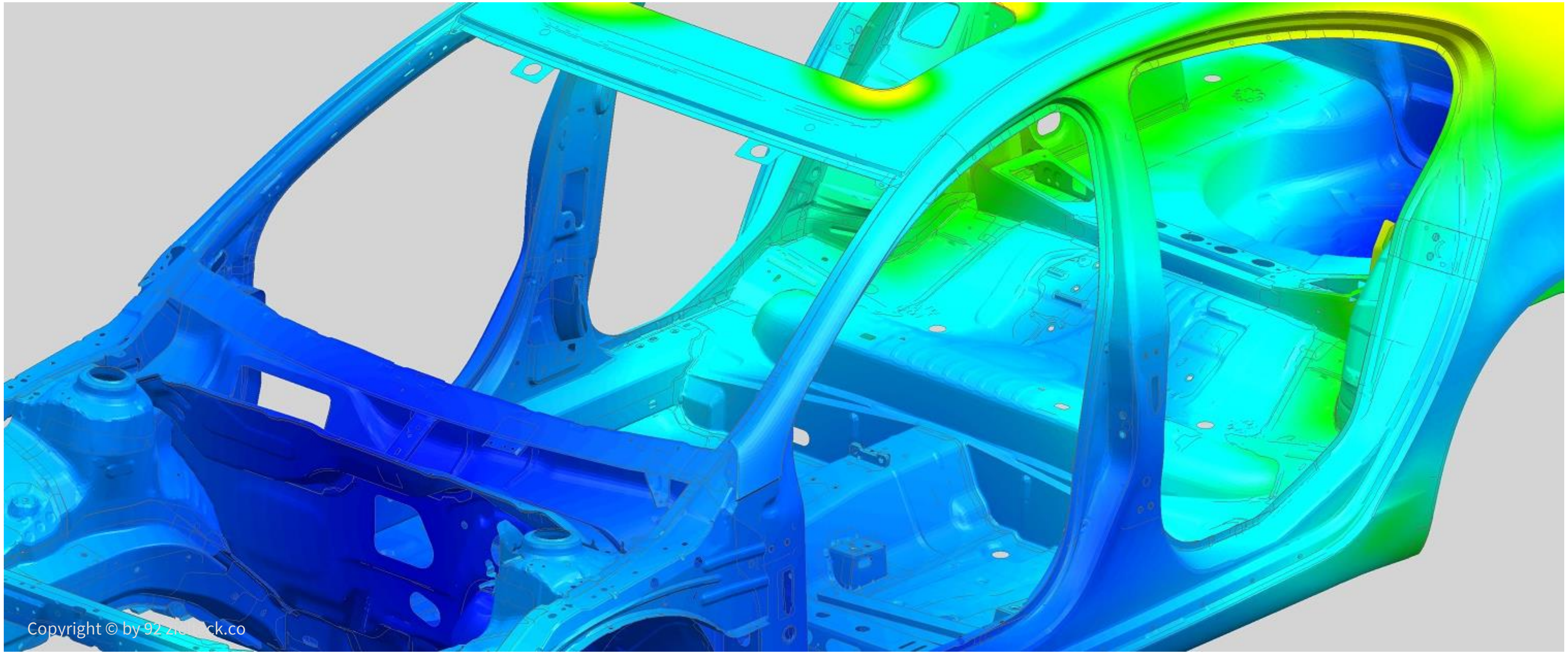
With the help of the Finite Element Method (FEM) and a load case assumed especially for the "bridge section biotope", the frame design was carried out for the conceived masses as well as their applied points of application.

The efficiency and space advantages resulting from the biotope character and the modular design were exemplified by the wheel assembly.

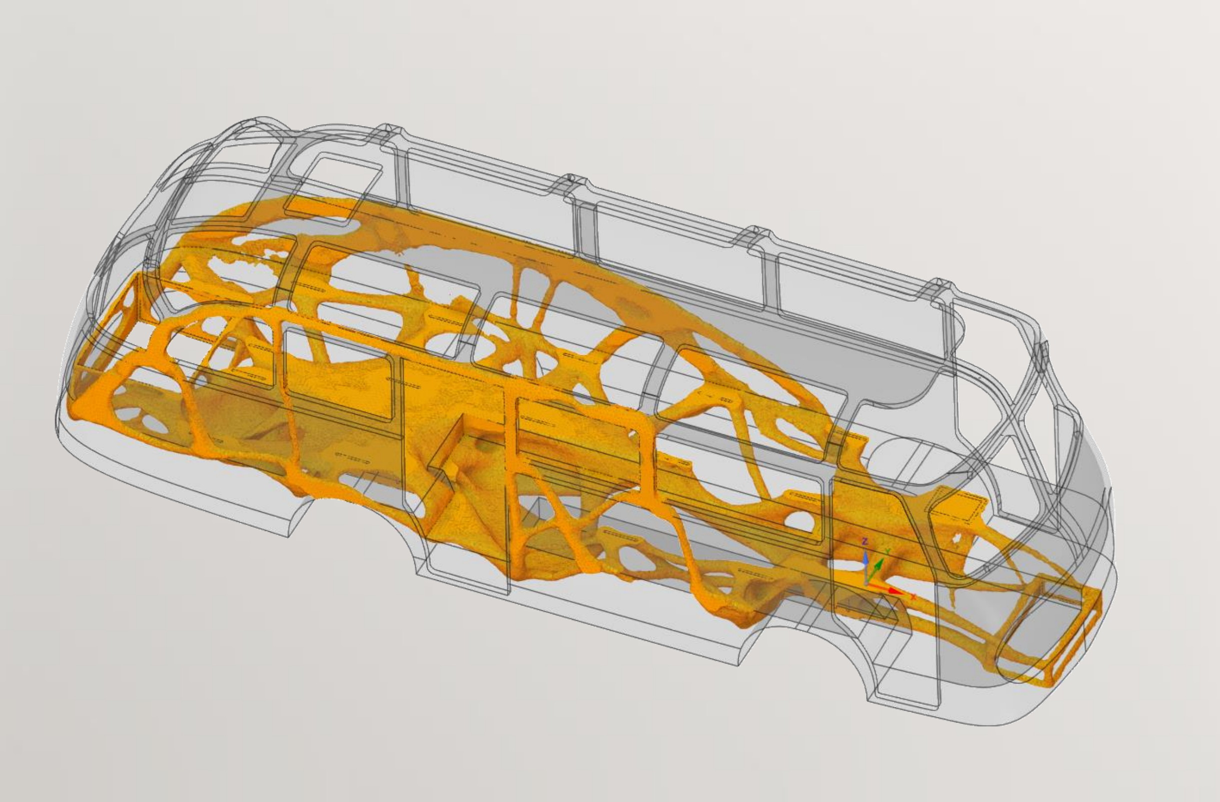
A powertrain simulation was developed in order to be able to make a statement about the technical key data of the electric motors, the associated transmissions and the energetic load profiles of (buffer) batteries. For the present concept, numerous input parameters such as vehicle mass, maximum speed, driving resistance, etc. were determined, which enabled a reliable calculation of the required output variables.

Optimized weight distribution for all components of a vehicle means less drive energy required

The vehicle fleet on the bridges is manufactured in lightweight construction. In order to make all components as light as possible, the loads on numerous components are determined using the finite element method. In this way, structures are manufactured that are designed in such a way that they can absorb the forces that occur, but no material is unnecessarily wasted. The result is specialized parts that are nearly ideal for their respective application and thus very light.



The Neoplan NH 6/7 is one of the larger vehicles on the bridges: Topology optimization was carried out for it



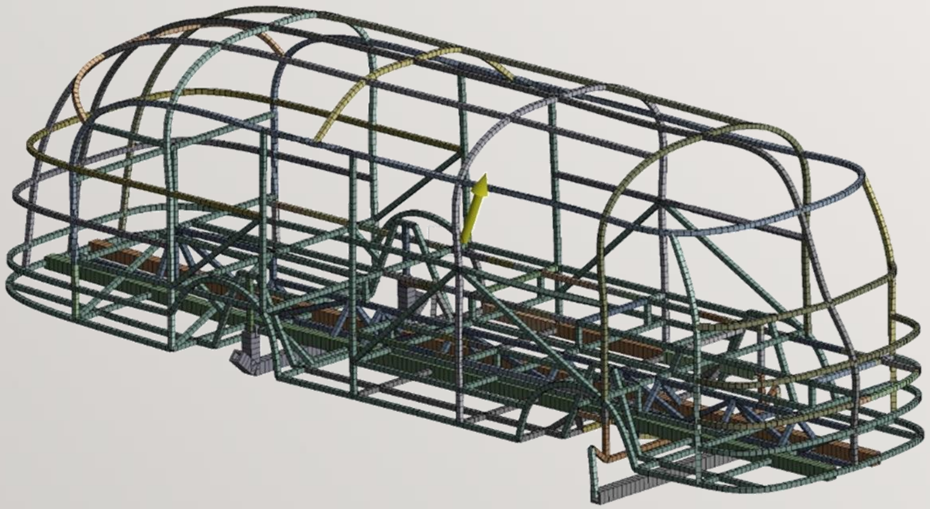
A topology optimization was carried out for the concept of the frame structure.

Within the available installation space, an organically acting structure is created here, which, depending on the load and bearing, suggests optimal force flows.

Even if such a structure cannot be finished directly, it provides valuable information for the actual design. This should then have an optimum ratio of weight to strength or stiffness.

In the early concept phase, the focus was on innovative methods

First, a frame structure was therefore designed for the Neoplan NH 6/7 in order to be able to carry out an FEM analysis as an example



In order to be able to adapt the resulting concept perfectly to the conditions of the bridges, it was optimized using the finite element method (FEM).

In this process, specific load cases are considered that reflect cyclic - i.e. everyday - loads on the one hand and extreme cases such as collisions on the other.

With the aid of the FEM, the frame was developed to be stable and weight-saving. In this way, safety and load-bearing capacity can be guaranteed despite the lightweight construction.

For the design of the frame structure, a simple beam model was used for the FEM analysis. This offers the advantage that changes can be easily incorporated during the development phase and the calculation time is much shorter compared to a detailed 3D model.

The requirements for the frame of the bridge Neoplan NH 6/7 were defined

The frame of a vehicle consists of rectangular steel or aluminum profiles. These are bent and welded in certain shapes so that the frame is resistant to various forces.

The forces acting in the frame structure result from the accelerations and point masses.

The masses represent relevant components in the interior, such as various aggregates and tanks, but also passengers, seat benches and also windows and trim panels.

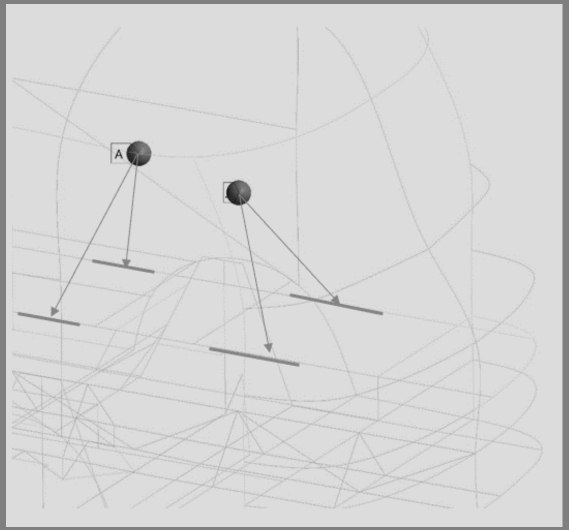
The point masses (represented as spheres) are attached to the frame as realistically as possible using 1D elements. In this way, the resulting forces and moments are correctly represented.

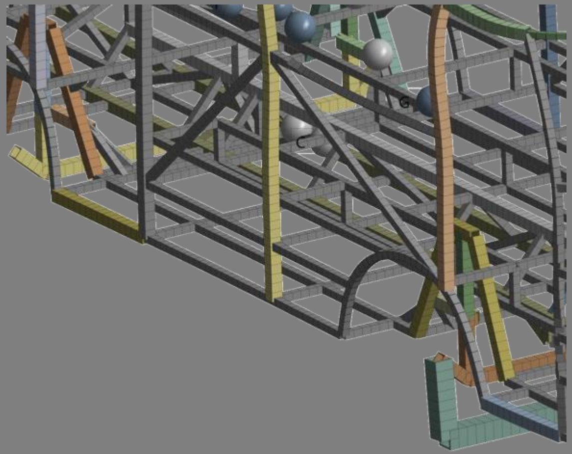
This model can also be used to simulate the deformation of the frame under load.

All masses, such as seats, tanks or even the planking and glazing, were represented as point masses (spheres) and connected to the frame structure.

All connections have been taken into account in the frame structure of the bridge neoplan

This connection is shown as an example for the driver's seat and another seat.





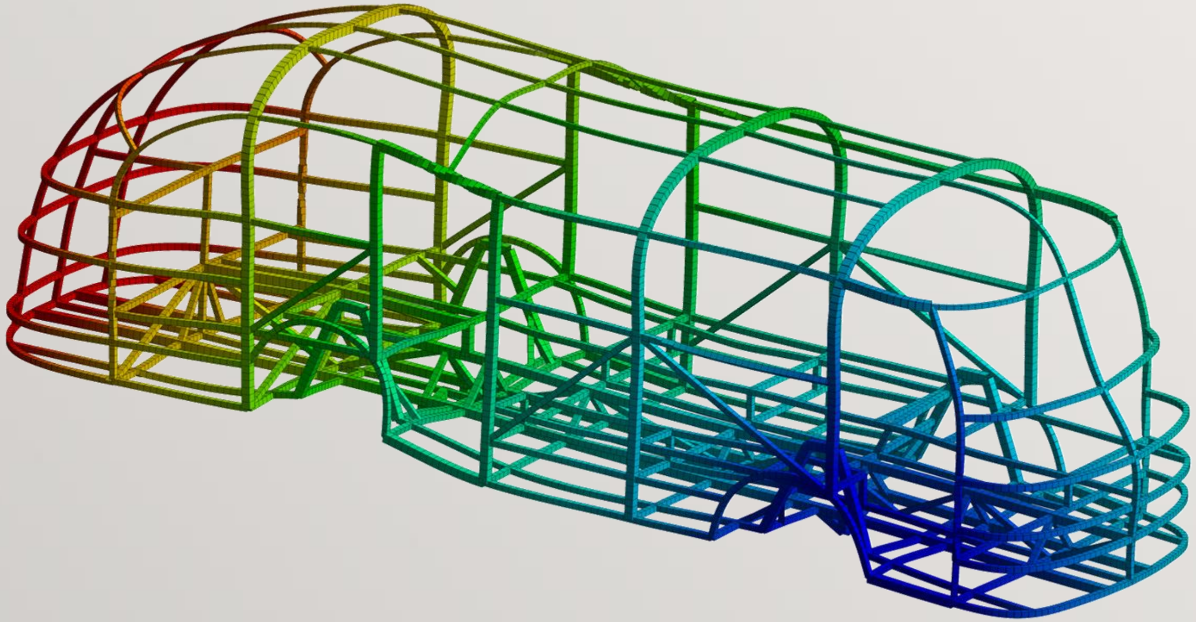
The load case under consideration involves a combination of quasi-static loads due to braking, sleeper crossing, pothole crossing, cornering and dead weight

A rocker was designed for the bearings of the frame structure on the front axle. Together with the bearings on the rear axle, this provides the most accurate kinematics possible.

The kinematics of the chassis were also realized using joints. The cross-sections of the individual beam elements were parameterized. In this way, it was possible to achieve as uniform a degree of utilization as possible over many iterations.

Frame structure - calculation results of maximum deformation

The maximum deformation that occurs under the described load case is shown here. However, the degree of utilization of the structure is primarily relevant. The degree of utilization is determined via a program code with analytical formulas. This is based on the FKM guideline.



If the vehicle is braked or accelerated jerkily, the frame must withstand these forces.

Driving over a threshold or tight cornering must also be taken into account. These assumptions are bundled in a combined load case:

Acceleration	Value	Einheit
Max. Acceleration		
Acceleration x	800	mm/s^2
Acceleration y	600	mm/s^2
Acceleration z	3000	mm/s^2

```
/com,************* Berechnung nach der FKM-Richtlinie*******************
/com,*******************************************************************
/com, 1. Werkstoffkennwerte (für Stahl)
/com, Druck- und Schubfestigkeitsfaktoren
f_sigma=1
f_tau=0.577

! Normwerte
K_dm=1
K_dp=K_dm
K_A=0.83
R_mN=1255
R_pN=800

R_m=K_dm*K_A*R_mN
R_p=K_dp*K_A*R_pN

/com,Entfestigungsfaktor
rho_WEZp=0.63
rho_WEZm=0.72

/com, 2. Sicherheitsfaktoren
j_ges=1.35                     !würde 1.35 sagen, statt 1.8


*get,SEC_num,ELEM,1,ATTR,SECN
                               ! Querschnittdaten für das Element auslesen, wenn es sich um keine Schweißnah
*get,B,SECP,SEC_num,DATA,1     ! Breite
*get,H,SECP,SEC_num,DATA,2     ! Höhe
*get,t1,SECP,SEC_num,DATA,3    ! Wanddicke in der Breite
*get,t3,SECP,SEC_num,DATA,5    ! Wanddicke in der Höhe
n_pl=1.5*((1-(((B-2*t1)/B)*((H-2*t3)/H)**2))/(1-(((B-2*t1)/B)*((H-2*t3)/H)**3)))

/com, Der plastische Faktor ist %n_pl%

/com, 4. Bauteilfestigkeit
/com, Grundwerkstoff
S_SKzd=f_sigma*R_p
S_SKby=f_sigma*R_p*n_pl
S_SKbz=f_sigma*R_p*n_pl
/com,  Wärmeeinflusszone
S_SKzdWEZ=f_sigma*R_p*rho_WEZp
S_SKbyWEZ=f_sigma*R_p*n_pl*rho_WEZp
S_SKbzWEZ=f_sigma*R_p*n_pl*rho_WEZp
! Fakor mit dem die wirkende Spannung multipliziert werden muss, um den Auslastungsfaktor zu erhalten
S_KB_SKzdWEZ= j_ges/ S_SKzdWEZ
S_KB_SKbyWEZ= j_ges/ S_SKbyWEZ
S_KB_SKbzWEZ= j_ges/ S_SKbzWEZ

! Lastfälle berechnen.
*do,j,1,16
set,%j%    ! Die Daten aus dem jeweiligen Lastfall auslesen              ! Die ausgelesenen Daten sind nur
ESEL,S,ENAME,,188  ! Alle Balkenelemente Beam188 auswählen

etable, sdirI, smisc, 31
etable, sbytJ, smisc, 37
etable, sbybI, smisc, 33
etable, sbybJ, smisc, 38
etable, sbzbI, smisc, 35
etable, sbzbJ, smisc, 40

smult,a_zdI%j%,sdirI,,S_KB_SKzdWEZ    ! wenn es sich um eine Tabelle handelt an die 2. Stelle schreiben !!!
smult,a_bybI%j%,sbybI,,S_KB_SKbyWEZ
smult,a_bybJ%j%,sbybJ,,S_KB_SKbyWEZ
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PRETAB,a_zdI%j%,a_bybI%j%,a_bybJ%j%, a_bzbI%j%, a_bzbJ%j%

*ENDDO
/nopr
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Frame structure - variable structure of the geometry

Due to the parametric structure of the frame structure, it is also possible to react quickly to new requirements in the further course of development.

The growing level of detail of the parts that have not yet been designed can also be taken into account over time, for example by locally adjusting wall thicknesses or excluding evaluation areas if these are otherwise secured.

Acceleration values for the design of the Neoplan NH 6/7

Since the vehicle moves in a three-dimensional world, it also experiences accelerations in all spatial directions.

Acceleration	Value	Unit
Max. Acceleration		
Acceleration x	7,8	m/s^2
Acceleration y	5,9	m/s^2
Acceleration z	29,4	m/s^2
Cycl. acceleration		
Acceleration x	2,9	m/s^2
Acceleration y	2,0	m/s^2
Acceleration z	12,8	m/s^2

If the vehicle is slowed or accelerated suddenly, the frame must withstand these forces.

Here, there are accelerations that occur regularly, i.e. during everyday operation, and those that occur rarely, mainly in emergency situations. Both were considered in different ways.

The modular design of the vehicles on the Frankfurt bridges enables components to be replaced quickly and easily, thus ensuring permanent modernization

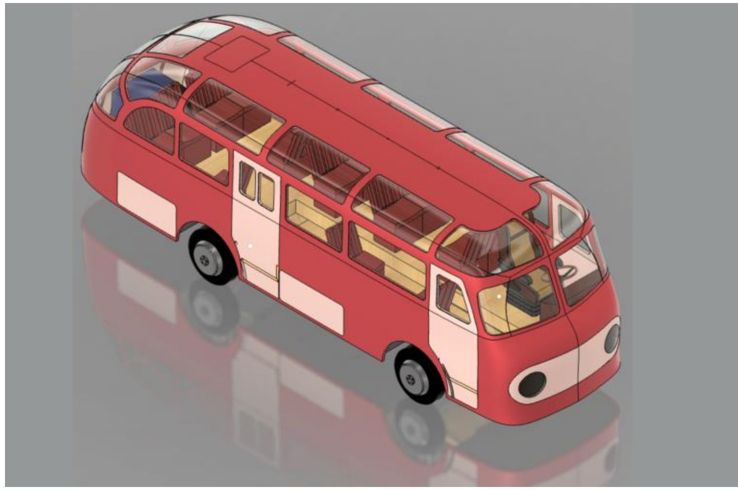
With a planned service life of one hundred years, technical progress must also be taken into account.

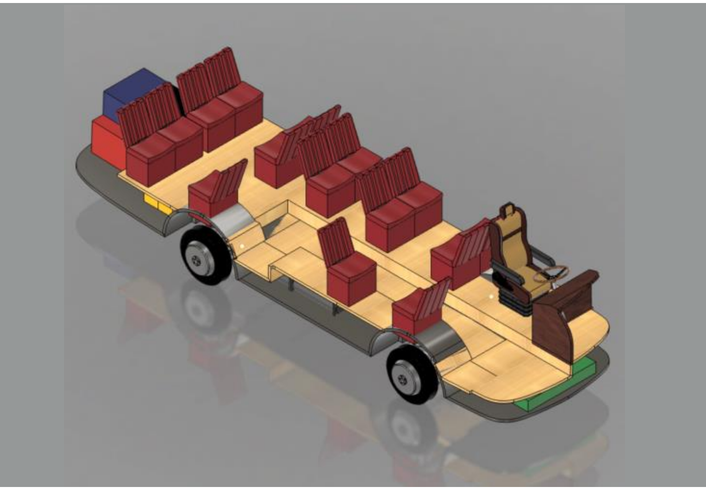
Thanks to their modular design, the cars can be easily modernized - by simply replacing the outdated components with newer ones, without having to replace the entire vehicle. For example, the powertrain can be replaced if other types of drive become established.

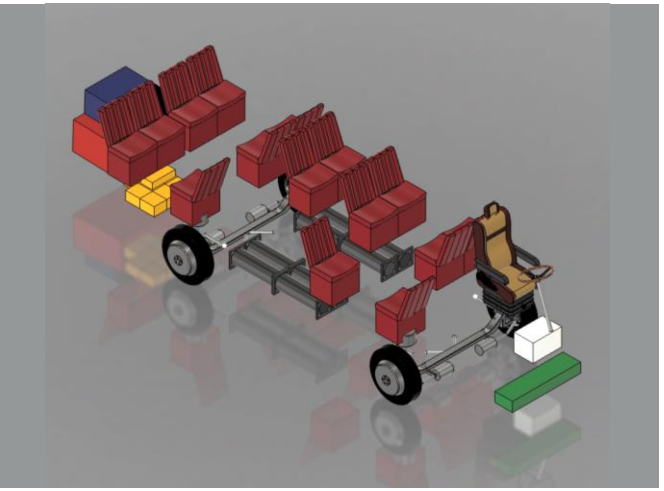
Everything else about the vehicle is retained in a resource-saving manner.Last but not least, there is another important factor that contributes to the longevity of the vehicles: There will be hardly any, not to say no more accidents, as all vehicles are forward-looking on the road.

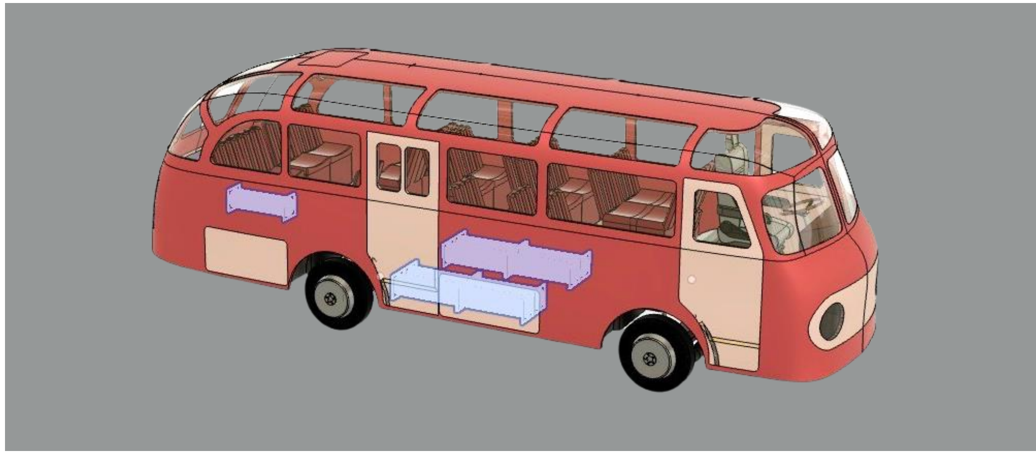
With 400 different trains, buses and cars, it is not possible to develop each vehicle individually

In the modular design, you have the lower frame as a component on the one hand, and the "hat" as a component on the other, which is placed on top. The interior in between can be filled with the required modular components - in the case of a hydrogen-powered vehicle, for example, these would be the fuel cell, tank, battery, chassis, electronics, and so on.









Altes Neuland
Frankfurt

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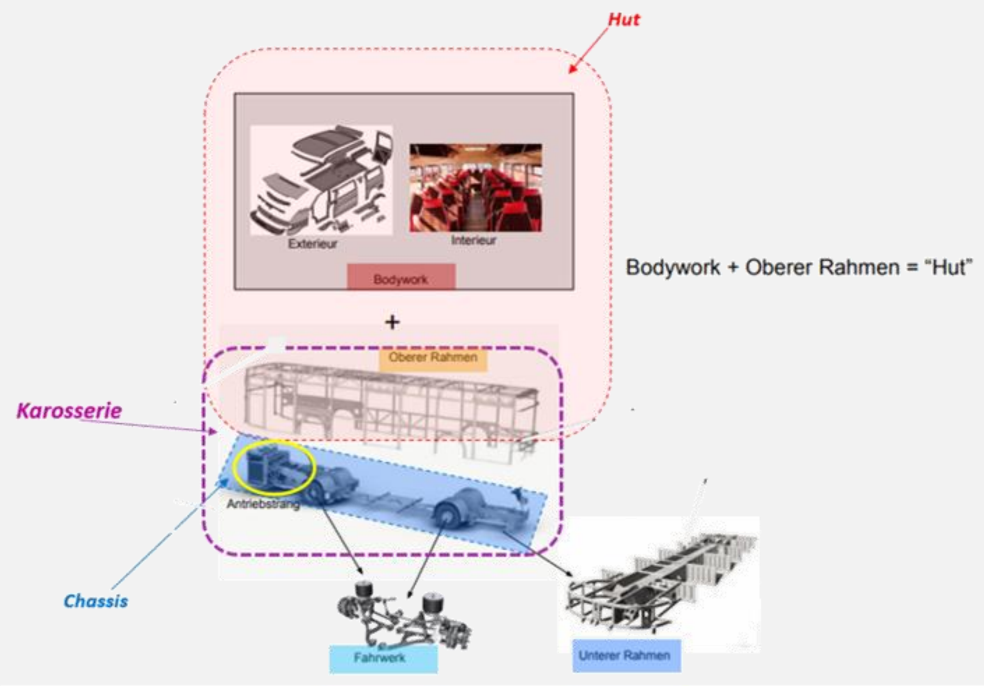
The concept of modular components inside a vehicle creates flexibility in the external form: The future of vehicle construction?

With the modular concept, it is possible to build many variants and Oldtimer bodies (such as different vintage cars) that are the same structurally and from the internal arrangement of the technical modules: A colorful diverse fleet of vehicles is created without having to develop each vehicle from scratch.

Should the number of vehicles in cities decrease in the future due to autonomous driving becoming the norm with urban vehicle fleets, then it will become attractive for the automotive industry to rely on varied vehicle designs that are different on the outside but modular on the inside or structurally.



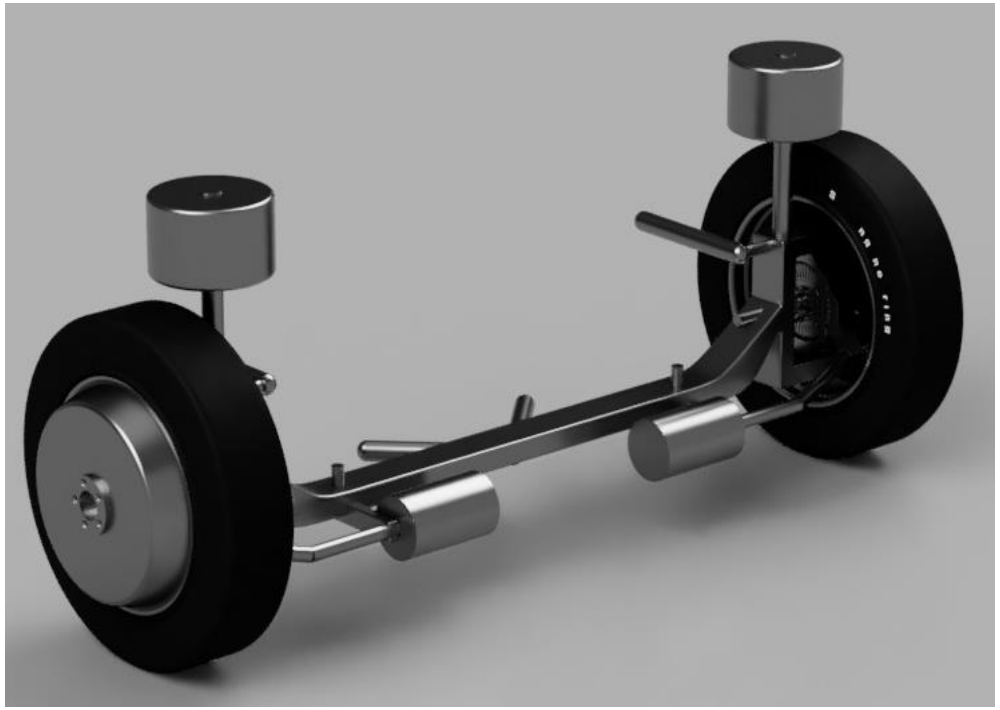
Each vehicle consists of individual modules that can always be rearranged

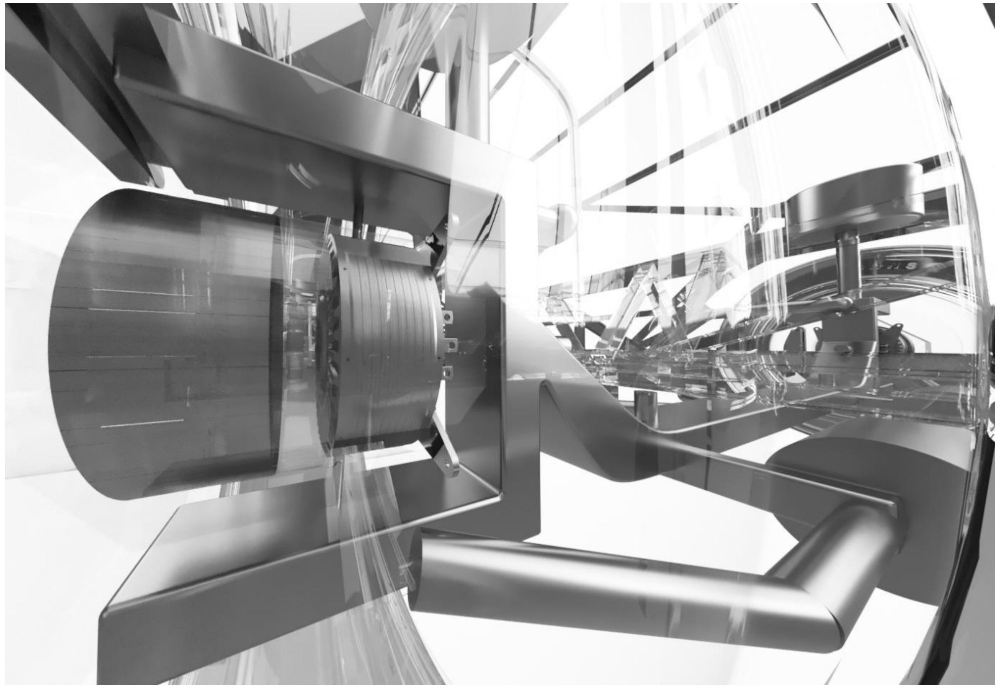
A good example of modularity is the wheel suspension. Tires, suspension and axle elements are always the same for vehicles of similar weight, but are made slightly wider or narrower and placed further forward or back. The advantage: A lot of time can be spent on optimizing the space and energy efficiency of each individual module.

The modular chassis reduces the development effort and minimizes the number of different spare parts required

Almost all vehicles on the Frankfurt bridges use the same chassis concept. A portal axle with wheel hub motors is installed, which makes it possible to use a particularly large amount of space in the interior.

By using this concept in all vehicle categories, the overall system only needs to be fundamentally designed once and is then only slightly adapted for each vehicle.In addition, an all-wheel drive system, air springs and all-wheel steering ensure a pleasant and efficient driving experience.



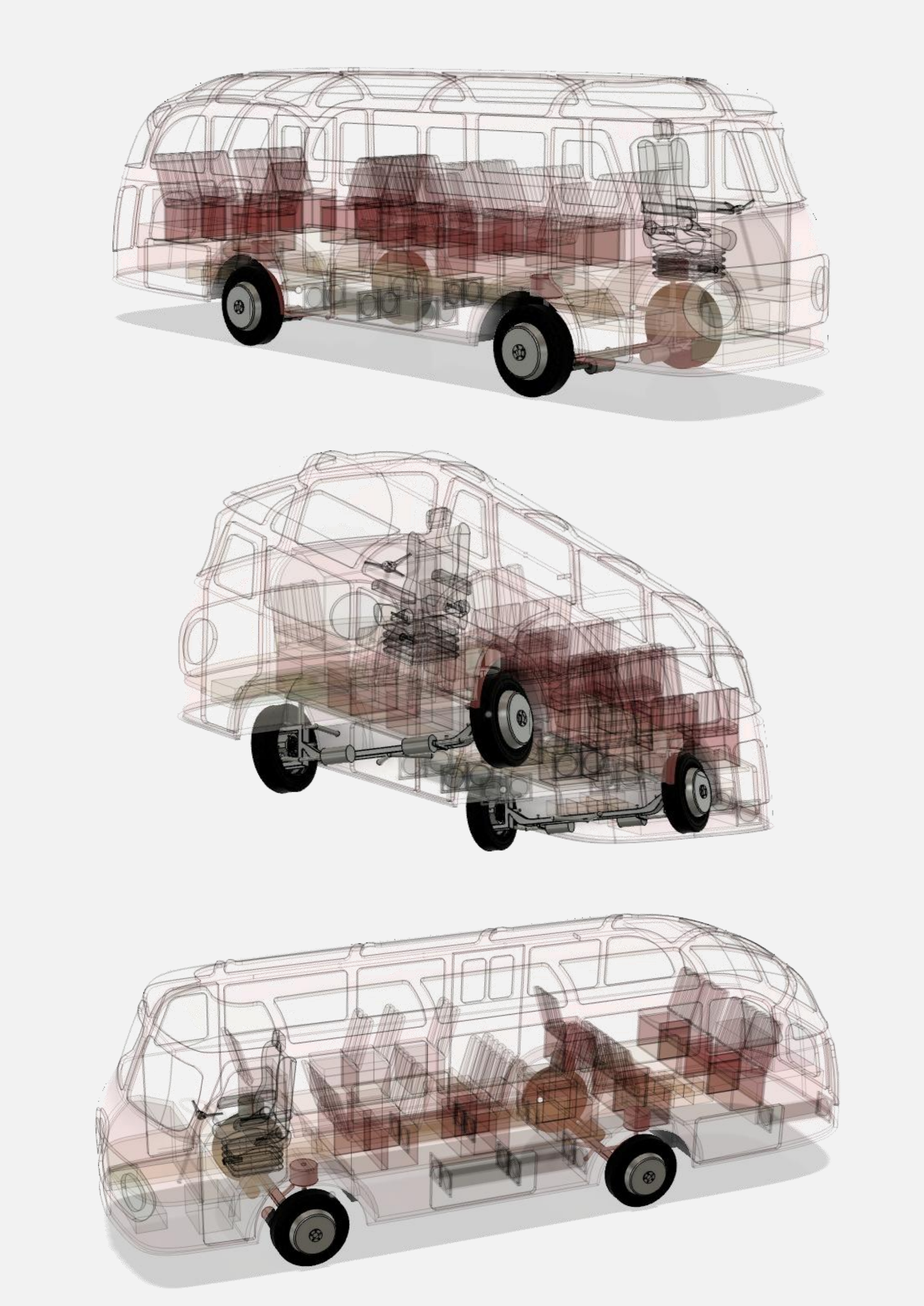


The wheel assembly combines the advantages of a four-wheel drive with those of wheel hub motors

The wheel assembly concept includes so-called wheel hub motors, which are located in the wheel hub. This technology is particularly well suited to the vehicles on the Frankfurt bridges because the classic disadvantage, namely the high unsprung masses, plays only a minor role.

Thus, because of the comparatively low speeds and accelerations on the bridges and because of the low weight of the buses, much smaller and thus lighter engines are used than in conventional road transport.

In addition to lower weight, such smaller engines have another advantage: There is plenty of space in the interior for passengers because the drive is located directly on the wheel.In addition, engines in all wheels make the vehicle maximally efficient in both propulsion and braking.



Air suspension ensures maximum ride comfort and adapts dynamically to the driving situation

The suspension of the vehicle is realized by air springs analogous to conventional systems in local passenger transport. This significantly increases ride comfort and reduces weight compared to steel springs. In addition, the vehicles can be lowered laterally at the stops for convenient boarding.

In addition, the spring rate can be flexibly adjusted while driving. Since the topography of the track is known and each vehicle is also permanently updated, this allows the suspension to be fine-tuned for each section and driving situation, starting from a basic setting.

Designation	Value	Unit
Body dimensions / wheel front axle	1.228,8	kg
Body dimensions / wheel rear axle	2004	kg
Spring constant Air spring front axle	109	kN/m
Spring constant Air spring rear axle	178	kN/m
Damping constant front axle	829	kNs/m
Damping constant rear axle	1.353	kNs/m

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For the design of the components in the chassis and assessment of the centre of gravity position, the dynamic wheel load displacement must be determined

A dynamic wheel load shift occurs during acceleration and deceleration as well as during cornering.

With these values, the components of the chassis can be designed according to the expected loads.

In addition, it is checked whether the position of the centre of gravity, which follows from the arrangement of the components, is within a safe range. This ensures that the vehicle has sufficient grip in all driving situations and is not at risk of tipping over in curves.

Driving situation	Center of gravity acceleration [m/s^2]	hs [m]	L [m]	COG y [m]	Fa1 [N]	Fa2 [N]
Cornering	0,10	1,12	2,10	0,02	40.899	40.019
Cornering	0,30	1,12	2,10	0,02	41.771	39.132
Cornering	0,50	1,12	2,10	0,02	42.643	38.244
Cornering	0,70	1,12	2,10	0,02	43.514	37.356
Cornering	0,90	1,12	2,10	0,02	44.386	36.469
Curve travel (standard load case)	1,00	1,12	2,10	0,02	44.822	36.025
Cornering	1,25	1,12	2,10	0,02	45.911	34.915
Cornering	1,50	1,12	2,10	0,02	47.001	33.806
Cornering	1,75	1,12	2,10	0,02	48.091	32.696
Cornering	2,00	1,12	2,10	0,02	49.180	31.586
Cornering	3,00	1,12	2,10	0,02	53.539	27.148
Cornering	4,00	1,12	2,10	0,02	57.898	22.709
Cornering	5,00	1,12	2,10	0,02	62.256	18.271
Cornering	6,00	1,12	2,10	0,02	66.615	13.832
Cornering	7,00	1,12	2,10	0,02	70.973	9.394
Cornering	8,00	1,12	2,10	0,02	75.332	4.956
Cornering	9,00	1,12	2,10	0,02	79.690	517

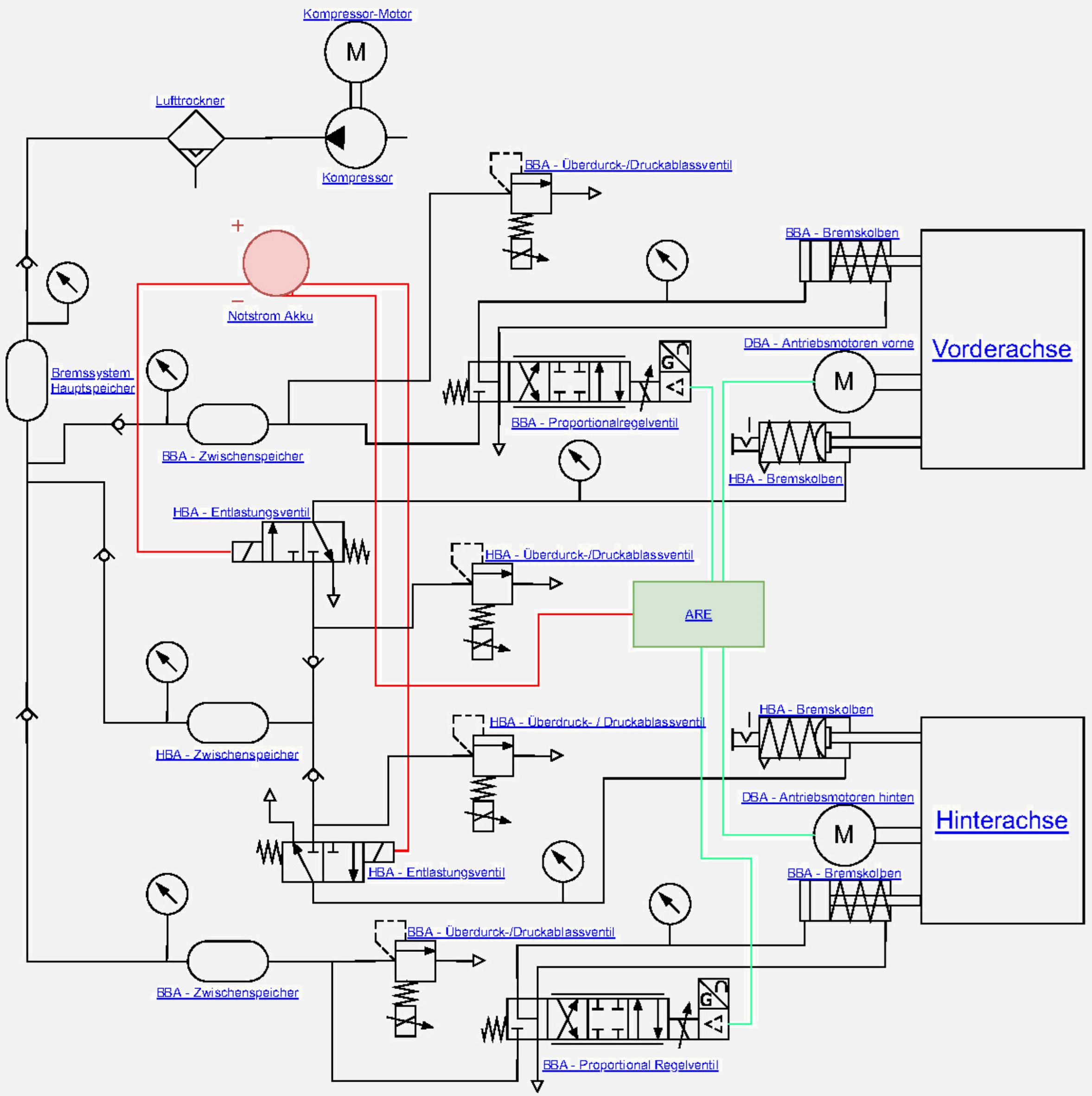
Gain energy while braking and still be safe on the road

Due to the electric drive on all wheels, the vehicles do not require mechanical brakes during normal operation. This maximizes energy efficiency and minimizes wear and tear and thus maintenance.

Since this system does not work in the event of a power failure, a pneumatic-mechanical backup system is installed which automatically brakes the vehicle in this case.

Together with the concave track shape, this ensures that the vehicle is in a safe condition at all times.

Braking concept with multiple redundancy levels for autonomous driving on the Frankfurt bridges



The speed is always adjusted in such a way that passengers do not find even tight curves nauseous

When driving a car on curvy roads, some people quickly become nauseous. This happens because the driver of the vehicle enters the bend at high speed or accelerates when leaving the bend.

The occupants thereby experience a high, so-called lateral acceleration. Experience shows that passengers in conventional local passenger transport are exposed to maximum lateral accelerations of approx. 2.0 - to 2.5 m/s^2.

On the Frankfurt Bridges, the autonomous system optimizes the speed of the vehicles in the curves so that the lateral acceleration is always below 1.5 m/s^2. This is possible without any special effort because the system knows the exact nature of all curves.

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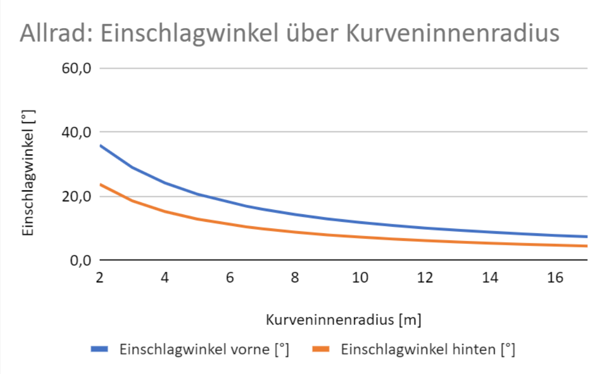
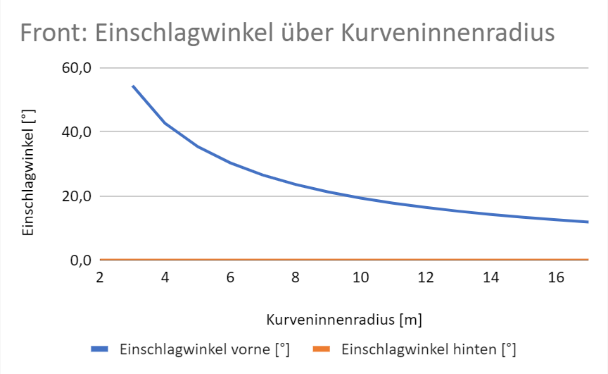
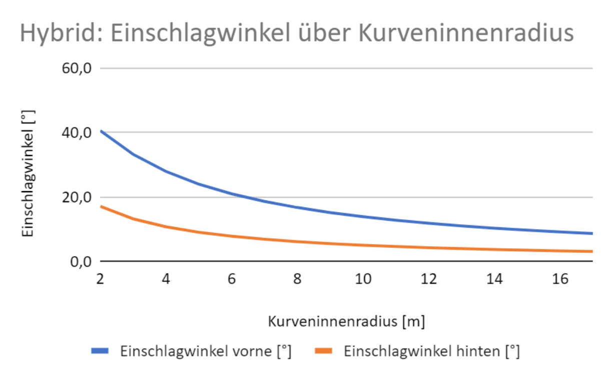
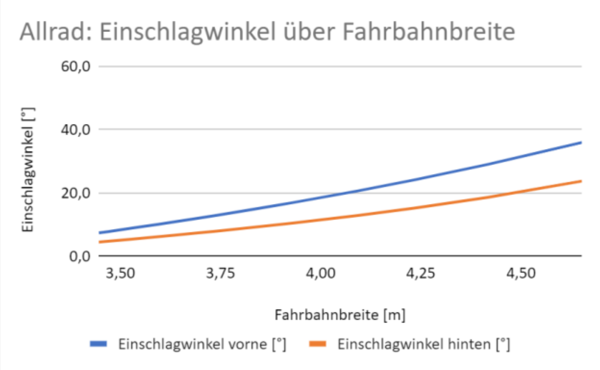
In order to use all advantages of possible steering concepts for the best possible and space-saving route on the Frankfurt bridges, different steering concepts were compared

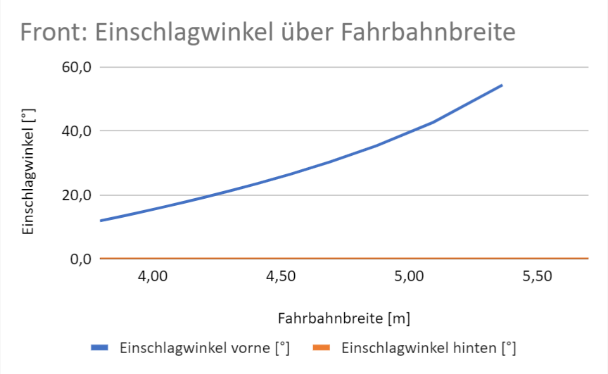
Typically, vehicles are steered by steering the front axle. However, it is also possible to steer the rear axle in order to negotiate tighter and narrower bends. For maximum driving comfort and ease of steering, vehicles use hybrid steering, which has a steering ratio of 0.7 between the front and rear axles. The influences of the steering angle on the inside radius of the bend and the width of the road are shown graphically for the individual steering concepts.

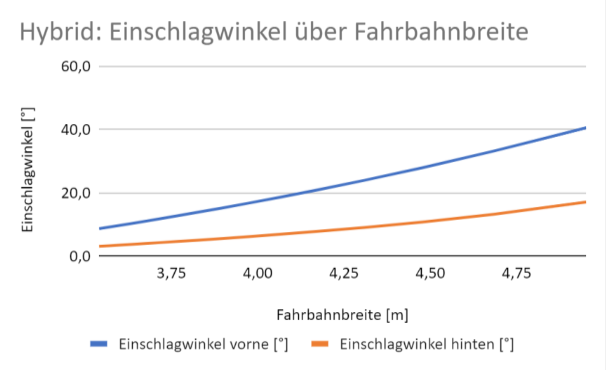












To plan the route on the Frankfurt Bridges, the dimensions of the towing curve of the largest vehicle were first calculated

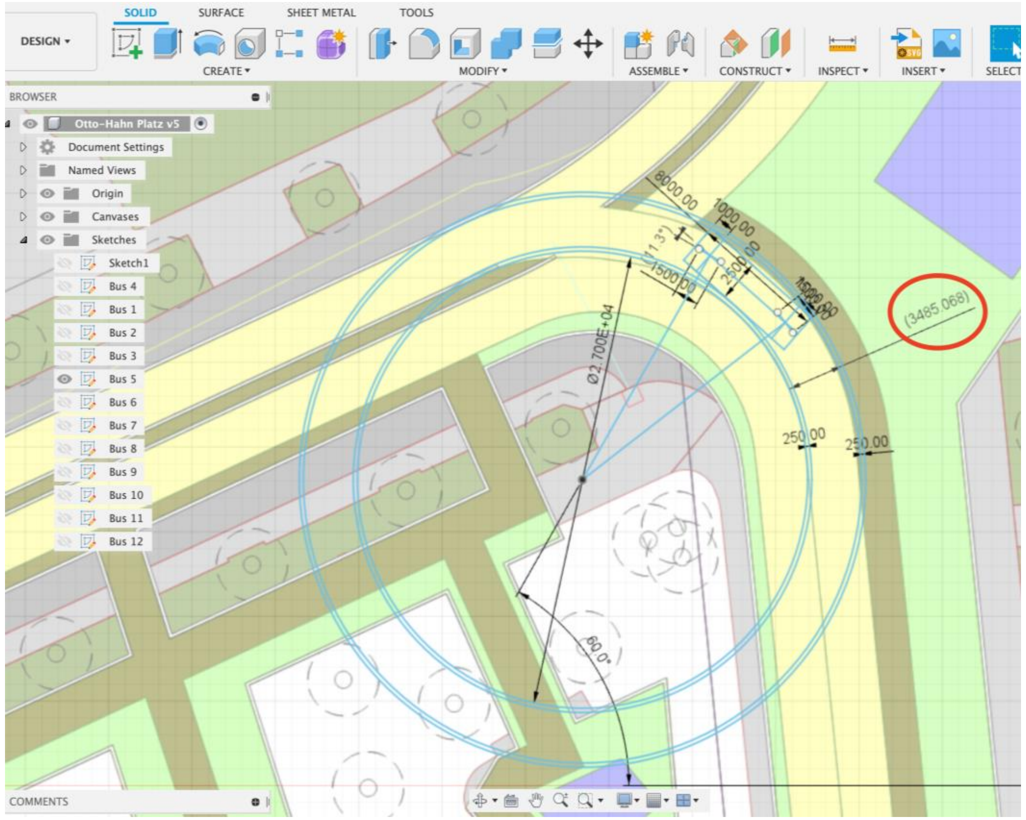
For a large vehicle to be able to drive around a curve, it must not be too narrow or too tight. For this reason, the towing curves of the largest vehicles on the Frankfurt bridges were determined precisely using geometric relationships. Not only the wheelbase but also the front and rear overhangs are relevant here. The data shown are valid for the Neoplan NH 6/7 model, which has the largest vehicle dimensions.

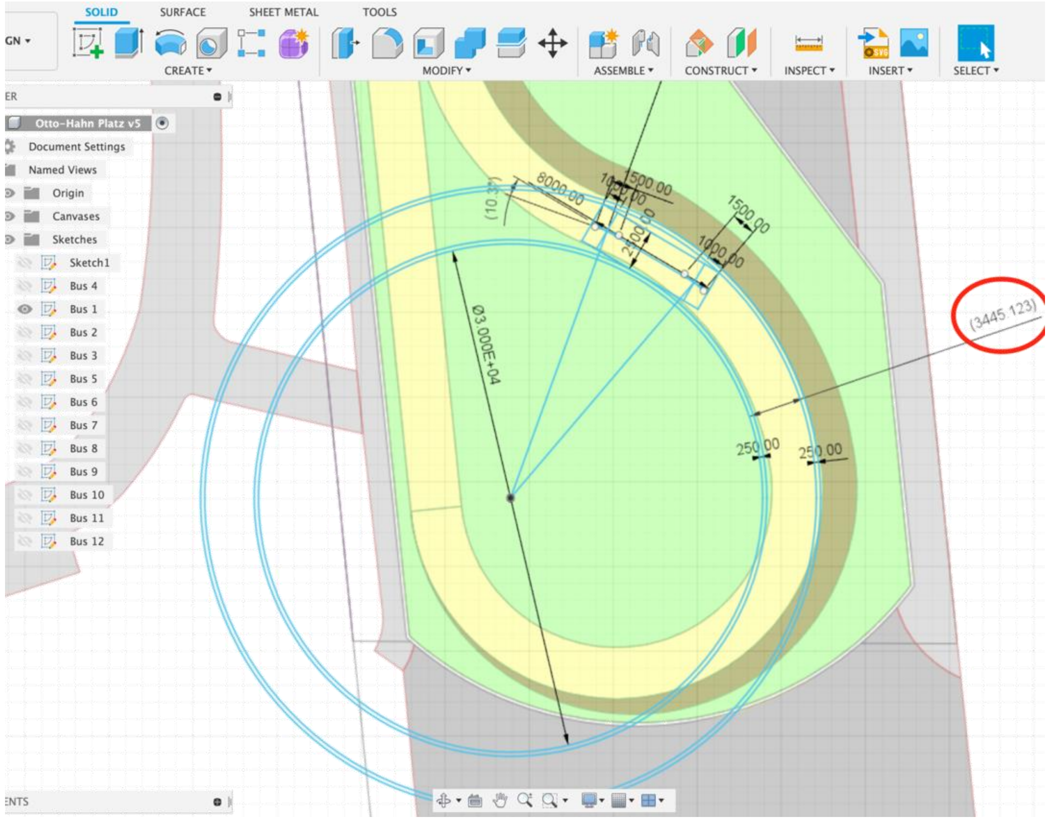
Input parameters	Value	Unit
Length	8,39	m
Wheelbase	3,78	m
front overhang	1,84	m
rear overhang	2,77	m
Vehicle width	2,5	m
Front axle to rear axle steering ratio	0,7	m

Calculation results	Value	Unit
inside curve radius of rear wheel	5	m
Front axle turning angle	24	°
Angle of lock rear axle	9,1	°
curve radius of the center of the curve	6,26	M
Turning circle diameter	15,19	m
Lane width	3,1	m

The route on the Frankfurt Bridges was planned according to the towing curves of the largest vehicles

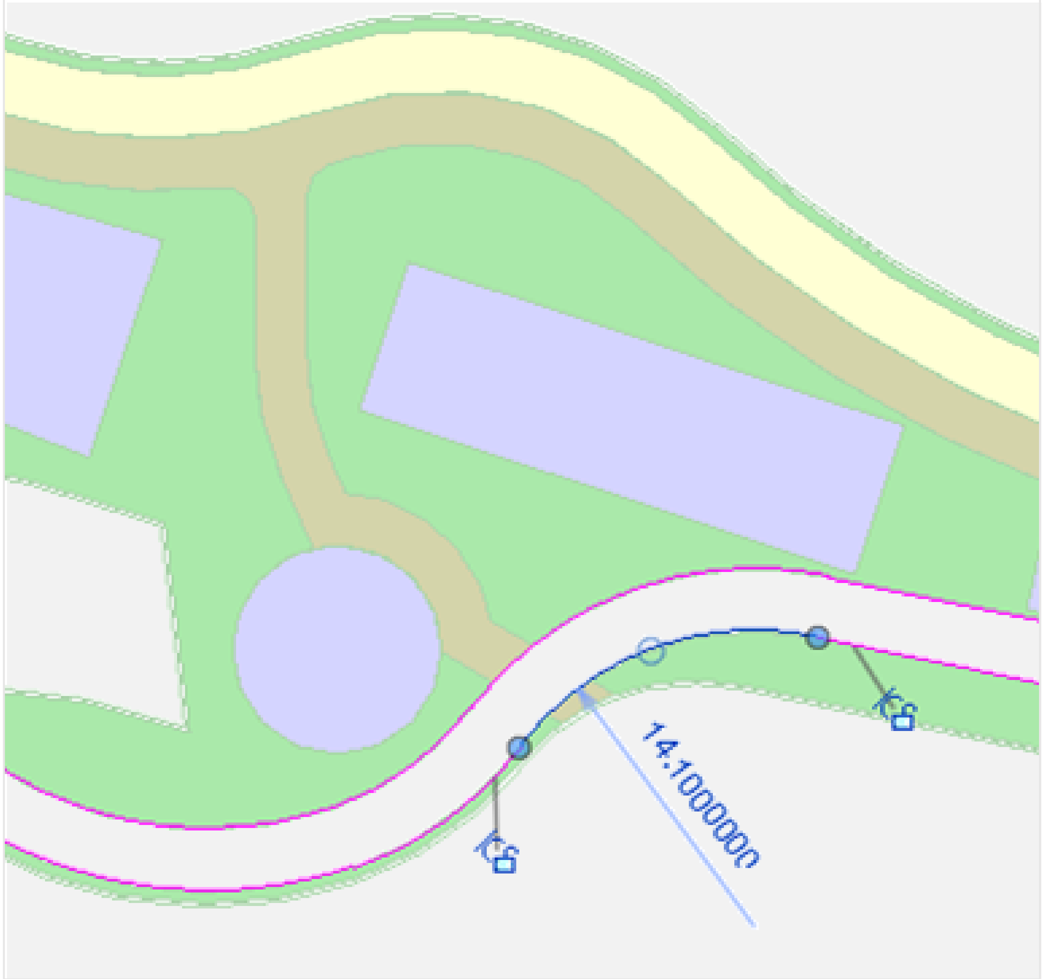
When planning the route, the radii and widths of the curves were created digitally and compared with the calculation results to ensure that the route is suitable for all vehicles.





The average speed of vehicles on the Frankfurt bridges is significantly influenced by the curve radii of the route.

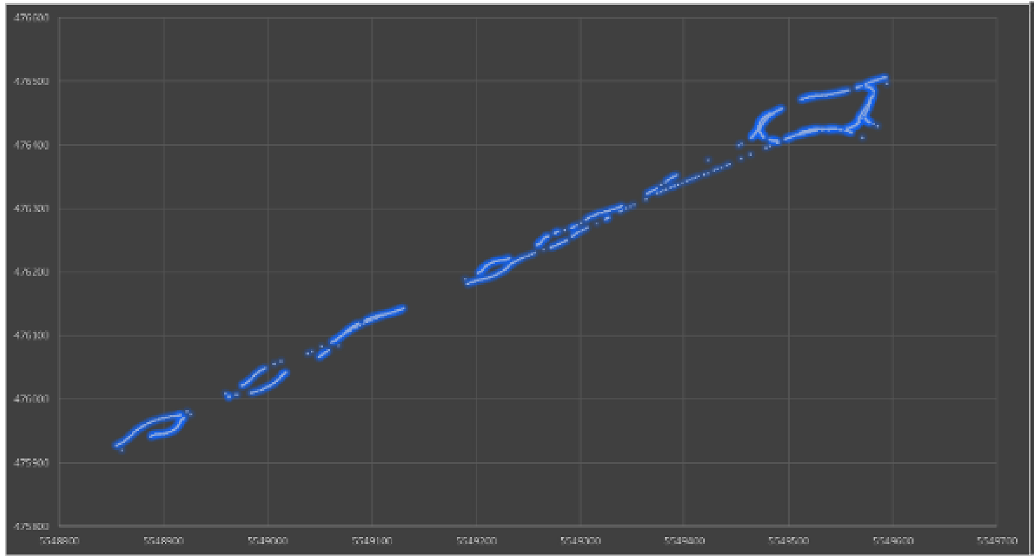
As part of the route development, the maximum speed at which the vehicles can drive through the curve was calculated. For this purpose, the tightest radii of numerous curves on the planned route were measured and calculated with the maximum permitted lateral acceleration.

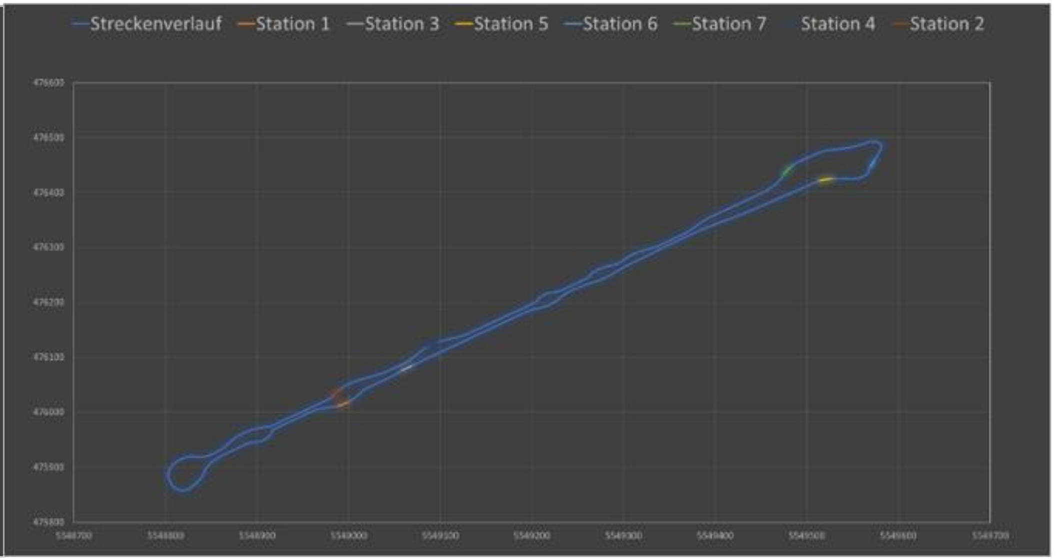


The course of the track in vertical direction also has a great influence on the dimensioning of the components and was taken into account in the simulation.

The raw data of the route planning, consist of two-dimensional points along the route and the information, at which of these points stations are located. These raw data must first be processed into usable route data, for which some scripts have been programmed.

The procedure is demonstrated below using Kennedyallee as an example. In order to create a circular route, points at Türmchenplatz, in particular the indicated arbe to Stresemannallee, as well as Kennedyallee further to the north-east were first removed. In addition, the route must be closed at the southwestern end. For this purpose, a semicircle can be used, which tangentially connects to the end points. However, this would result in a circle with a radius of only 4.4 meters, which is not consistent with the drivable radii of the vehicles. For this reason, the circuit is closed manually by two S-curves and a semicircle with a larger radius.





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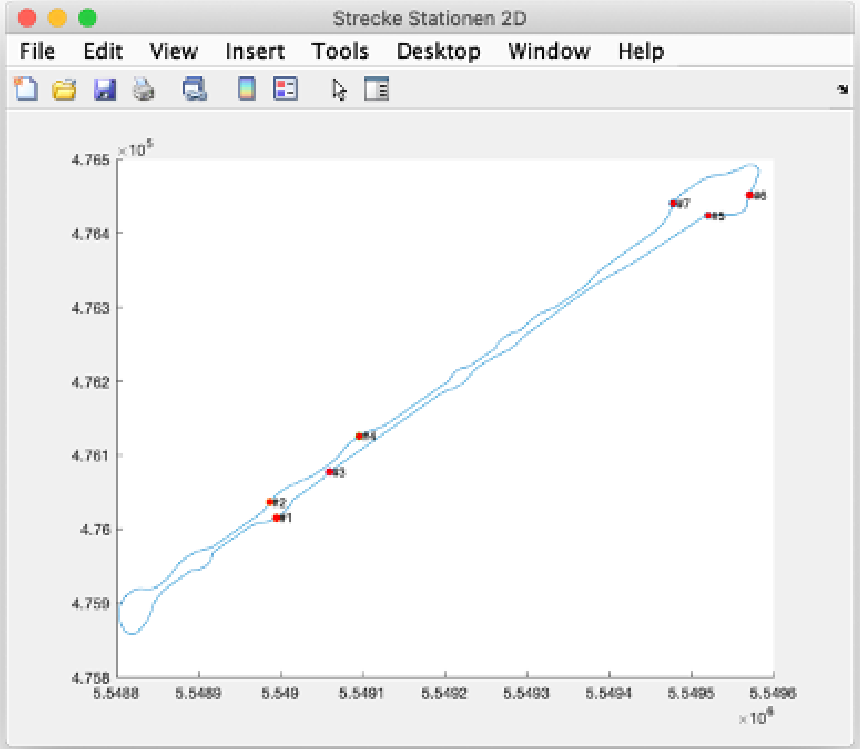
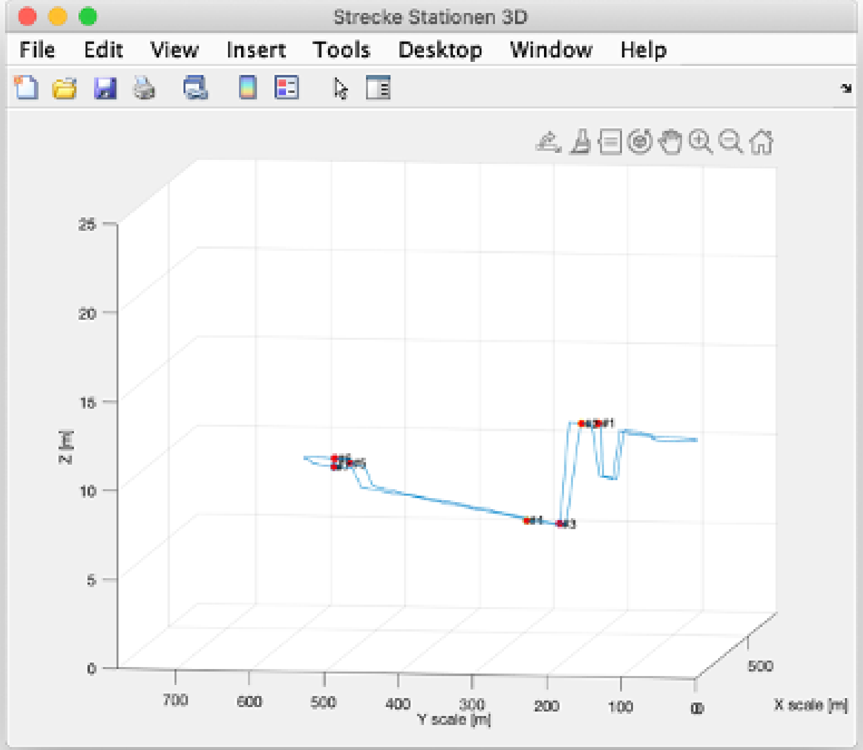
The course of the track in vertical direction also has a great influence on the dimensioning of the components and was taken into account in the simulation.

Since the route runs in the real world, not only two-dimensional coordinates have to be included in the route planning, but also the respective height of a point above sea level. On their way through Frankfurt, the vehicles have to drive up and down various inclines. The height data of these inclines are derived from the height profile of the ground and the bridge itself.



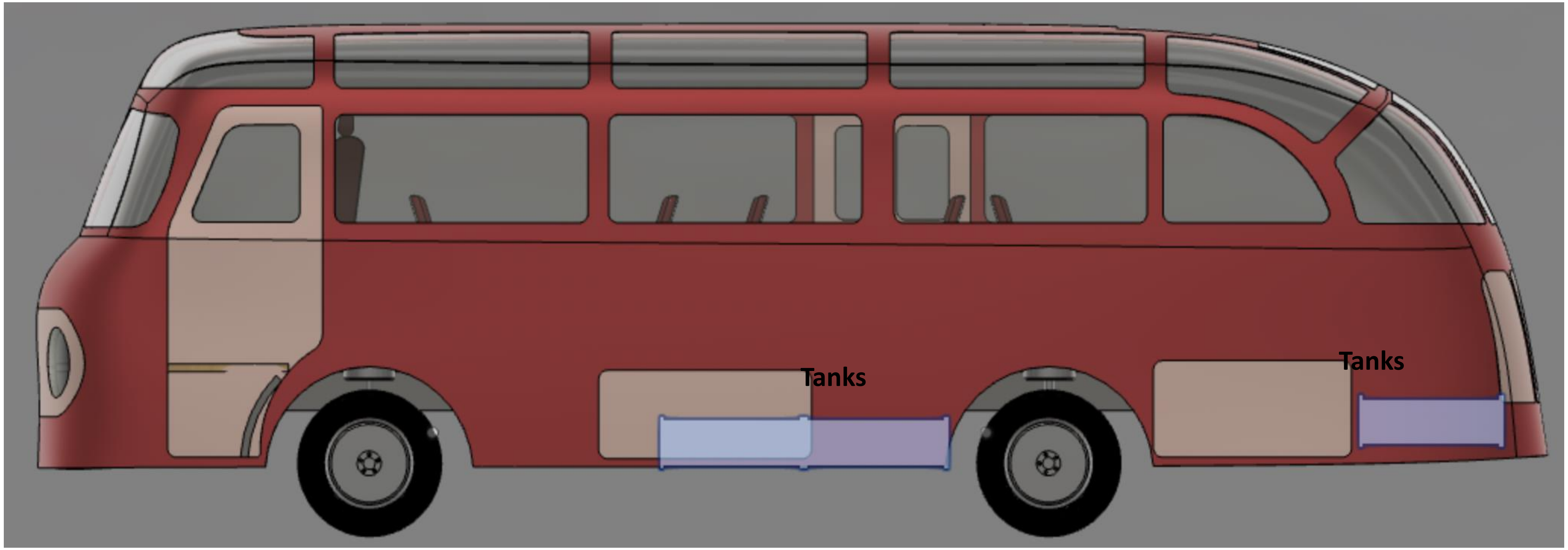


Due to the modular design, low centers of gravity can always be implemented for different models

The positioning of all components in the vehicle determines the center of gravity and thus also the driving dynamics. To ensure that the vehicles "lie on the track" as well as possible, all components were placed as far down as possible.

This keeps the vehicle from swaying as much as possible in curves and prevents it from tipping over. Many components can be arranged in a modular fashion to optimize driving dynamics.

Hydrogen tanks (blue), for example, are heavy and are housed in the double floor of the vehicle wherever possible. Large parts of the frame structure are also located there.



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Every design and every simulation calculation requires boundary conditions and parameters

Interior (cross-vehicle)	Value	Unit
Legroom	0,7	m
Seat width	0,5	m
Seat height	0,45	m
Seat depth	0,45	m
Backrest height	0,56	m
Aisle width	0,6	m

Vehicle dimensions NH 6/7 (vehicle-specific)	Value	Unit
Length	8,38	m
Wide	2,35	m
Height	3,78	m
Gauge	2,1	m
front overhang	1,84	m
rear overhang	2,77	m
Face	5,51	m^2
Tyre width	0,13	m
Wheel diameter	0,79	m

In order to make all design processes and calculations carried out as part of the concept as transparent as possible, all calculation assumptions and values were recorded in parameter lists.

Here there is a vehicle-specific parameter list, which contains all values that can be specifically assigned to a vehicle or that differ between different vehicles.

In addition, the cross-vehicle parameter list contains all values and boundary conditions that are valid across different vehicles.

On the left side, some cross-vehicle requirement values for the interior as well as the vehicle-specific dimensions of the Neoplan NH 6/7 are shown as examples.

The design of electric motors, batteries and hydrogen tanks is made possible by complex powertrain simulation

If one wants to make a statement about the required electric motors, batteries and hydrogen tanks, a simple consideration of the influencing variables is no longer sufficient, since the effects resulting from these variables cannot be determined immediately and can also change again and again.

For this reason, a complex simulation was developed into which the vehicle parameters such as external dimensions and weight are fed. In addition, the simulation knows all the necessary parameters of the route on the bridges, including gradient areas, stop waiting times, curves, etc.....

From this, if physical laws are applied correctly, forces can then be determined, which in turn can be converted into torques and power specifications of motors. In addition, the load profile of batteries and fuel cells can also be determined and hydrogen tanks can be dimensioned.

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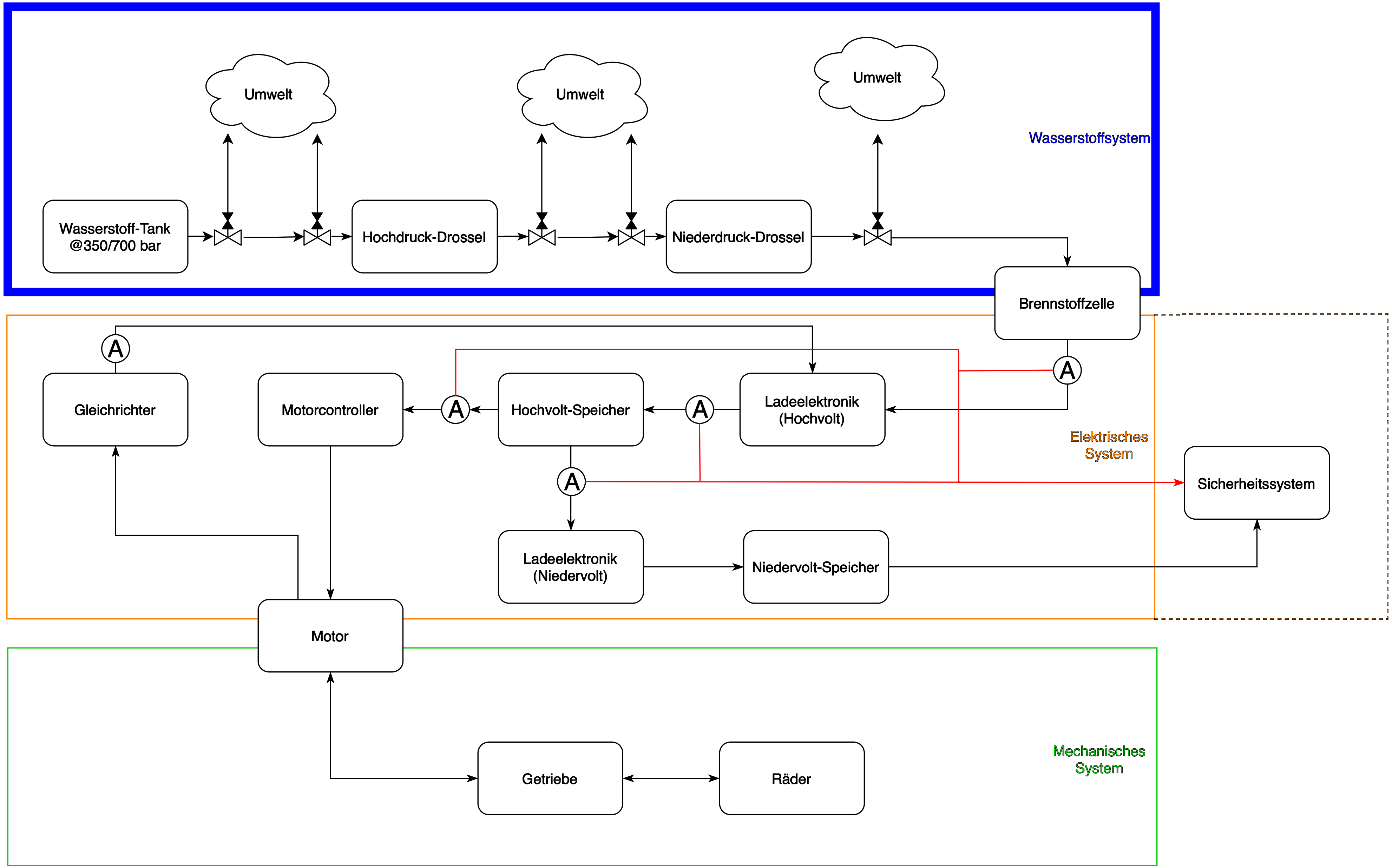


It is not only the installed drive components that influence energy consumption when driving, but also the weight. This results from the size of the engines, tanks and batteries.

In addition to the efficiency of the installed components, the weight of the entire vehicle is also decisive for the energy consumption and the further design of the vehicle.

In order to be able to quantitatively estimate the influence of the total vehicle weight on parameters such as energy consumption, engine torque and tank capacity, a corresponding analysis was carried out.

This shows that if the reference mass is changed from 10 t to 5 t, a reduction in hydrogen consumption in kg per 100 km from 7.82 to 6.55 can be achieved. Therefore, all vehicles should be designed in lightweight construction. This was done once as an example during the concept development for the vintage bus "Neoplan NH 6/7".

Mass of the NH6/7	H2 consumption	Unit
5000	6,55	Kg/100km
6000	6,81	Kg/100km
7000	7,06	Kg/100km
8000	7,32	Kg/100km
9000	7,57	Kg/100km
10000	7,82	Kg/100km
11000	8,08	Kg/100km
12000	8,33	Kg/100km
13000	8,59	Kg/100km
14000	8,84	Kg/100km
15000	9,09	Kg/100km
16000	9,35	Kg/100km
17000	9,60	Kg/100km
18000	9,86	Kg/100km
19000	10,11	Kg/100km
20000	10,37	Kg/100km

Drivetrain simulation allows both the wheel hub motors and the transmission to be designed

Engine speed, torque and other parameters can be determined on the basis of the powertrain simulation. Depending on the available components, suitable engines and transmissions can then be selected from the state of the art.

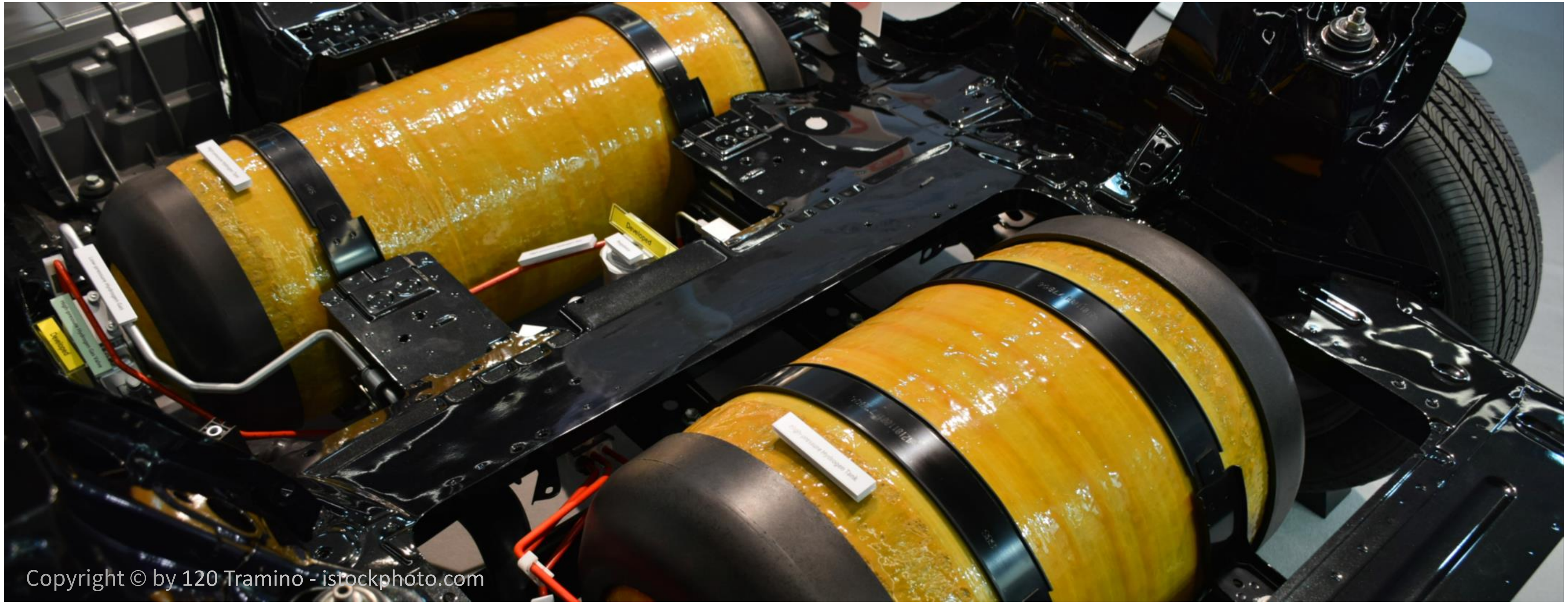
Input parameters	Value	Unit
Max. Torque per wheel	7114	Nm
Max. Power per wheel	3461 4	W
Max. Wheel speed	202	1/min
Average power amount per wheel	3211	W
Power share front axle	0,5	/
Safety factor	1,2	/

Technical data motor	Value	Unit
Max. Torque	90	Nm
Continuous torque	50	W
Max. Speed	6500	1/min
Continuous output	29000	W
Efficiency	0,94	/
Weight	7,2	Kg

Calculated gear ratio	Value	Unit
Min. gear ratio (from torque)	94,9	/
Max. Gear ratio (from speed)	32,3	/

The powertrain simulation allows the hydrogen consumption to be determined in advance and the hydrogen tank size to be specified.

The results from the powertrain simulation can be used to determine the hydrogen consumption per vehicle while driving along the route. Based on a specified operating time until refuelling or a certain number of kilometres, the required hydrogen tank size can thus be determined on a vehicle-specific basis. The vehicles on the bridges can drive for about 10 hours with their respective hydrogen tanks without having to refuel. The vehicles on the Frankfurt bridges use hydrogen tanks with a pressure level of 700 bar. This means that significantly more hydrogen can be stored in the same volume than with 350 bar systems.



For example, the approximate load profile of the buffer batteries of hydrogen vehicles was virtually determined by the powertrain simulation

While the drive energy for battery-electric vehicles is taken from the battery while driving, hydrogen-electric vehicles are supplied by a fuel cell. This converts the hydrogen from the tank and air into electrical energy and water during the journey.

In the powertrain simulation, a curve was determined using the example of the Neoplan NH 6/7, which indicates how much energy is required for which section of the route. For example, when a vehicle is driving uphill, there is a strong headwind and there are many passengers with heavy luggage in the passenger compartment, it requires a particularly large amount of energy.

Since a vehicle sometimes briefly consumes more energy than the fuel cell in the passenger compartment can supply, a small buffer battery is used that can provide this additional amount of energy. In this way, the fuel cell can be chosen to be as small as possible and as large as necessary. If the vehicle consumes little energy, for example because it is driving downhill, the excess power of the fuel cell is used to recharge the battery.

The buffer battery consists of two components

If the charging and discharging processes during the journey are analysed in more detail using the so-called rainflow algorithm, it becomes clear that a lot of energy is usually only released for a short time. In order to be able to make a decision as to which battery technology makes sense, certain boundary conditions must be taken into account.

In lithium-ion batteries, for example, a certain amount of energy can be extracted until the battery cell dies due to age or cycling. If the cycles are relatively small, more energy can be extracted overall than if, for example, the battery is always fully discharged. However, if the cycles are very small, the battery is constantly "hardly" loaded, which reduces the service life, although the capacity of the battery is not used sensibly.

Since the focus of the development concept is also on the longevity of the components, a combined energy storage concept is proposed for the "buffer battery": Very small cycles are handled via supercapacitors so that the battery is not loaded. Larger cycles are realized via the battery. In this way, the lifetime of the buffer battery is maximized and limited mainly by the aging of the battery cells over time.

The results of the powertrain simulation also make it possible to easily specify engine and transmission characteristics

The specifications of the engines as well as the transmission were determined for the example vehicle Neoplan NH 6/7 based on the results of the powertrain simulation. First and foremost, parameters such as the maximum torque per wheel, the maximum power per wheel and the maximum speed are taken into account.

These parameters are calculated with a safety factor and then result in the minimum requirements for the motor to be selected. In the next step, the performance data of various motors available on the market were researched and compared with the calculated requirements. If all requirements are met, the motor is considered suitable.

Input parameters from the simulation	Unit	Value
max. torque per wheel	Nm	2098
max. power per wheel	W	34613
max. wheel speed	1/min	201
average power per wheel	W	3211
Power share front axle	-	0,5
Safety factor	-	1,2

Based on the calculations, a suitable motor model was selected as an example

The gear ratio must also be determined in coordination with the engine characteristics.

The minimum permitted gear ratio is determined by the required torque, while the maximum permitted gear ratio is determined by the required speed.

The gear ratio of the selected gearbox must lie between these two values.

Technical data engine / gearbox	Unit	Engine model Emrax 188 (CC)
max. torque	Nm	90,0
Continuous torque	Nm	50,0
max. speed	1/min	6500,0
max. power	W	52000
Continuous output	W	29000
Efficiency	-	94%
Weight	kg	7,2
Min gear ratio (from torque)	-	27,97
Max gear ratio (from speed)	-	32,26
Resulting translation		30
Necessary cooling capacity motor	W	231

The energy consumption of a vehicle on the Frankfurt Bridges is strongly influenced by the air conditioning performance

Because of the lower driving speed, air resistance, for example, is of very little importance for energy consumption when driving, but air conditioning performance is of high importance. Therefore, special glasses were provided that can significantly reduce energy consumption. An excerpt from the analysis of what effects changes in a vehicle's air resistance have on, for example, hydrogen consumption can be found below.

Variation of the drag coefficient cw_A	Value	H2 consumption in kg per 100 km
Drag coefficient 1	0,5	7,76
Drag coefficient 2	0,75	7,77
Drag coefficient 3	1	7,79
Drag coefficient 4	1,25	7,81
Drag coefficient 5	1,5	7,82
Drag coefficient 6	1,75	7,84
Drag coefficient 7	2	7,86

The table shows the effect of a change in air resistance on hydrogen consumption in kg per 100 km.

This clearly shows that air resistance has a negligible influence on consumption for vehicles on the Frankfurt Bridges.

Therefore, even a "simple" component, such as the air conditioning system, must be designed

Many different factors must be considered when designing components. The more boundary conditions there are, the more difficult it is to select a correct component. For example, in order to be able to make a statement about the required air conditioning system, the solar radiation in Frankfurt, the expected specifications of the glass in the vehicle, the associated surfaces and the heat emitted by passengers were determined.

From this, the heat that is introduced into the vehicle and thus the required air conditioning output can be determined. In addition, the air conditioning output can be reduced by using modern materials.

Input parameters	Value	Unit
Inside temperature	25	°C
Outdoor temperature	38	°C
Number of passengers	26	/
Total area sheet metal	32	m^2
Total area glass	19	m^2
Max. Global radiation Frankfurt	3800	kJ/m^2/h
Glass coefficient (G-value)	0,6	/
Thermal input power by sun	14,6	kW
Power requirement air conditioning	4,9	kW

Various parameters are included in the air conditioning design. Examples of these are the sheet metal and glass surfaces of the vehicle as well as the insulation values of the installed glass and insulating materials.

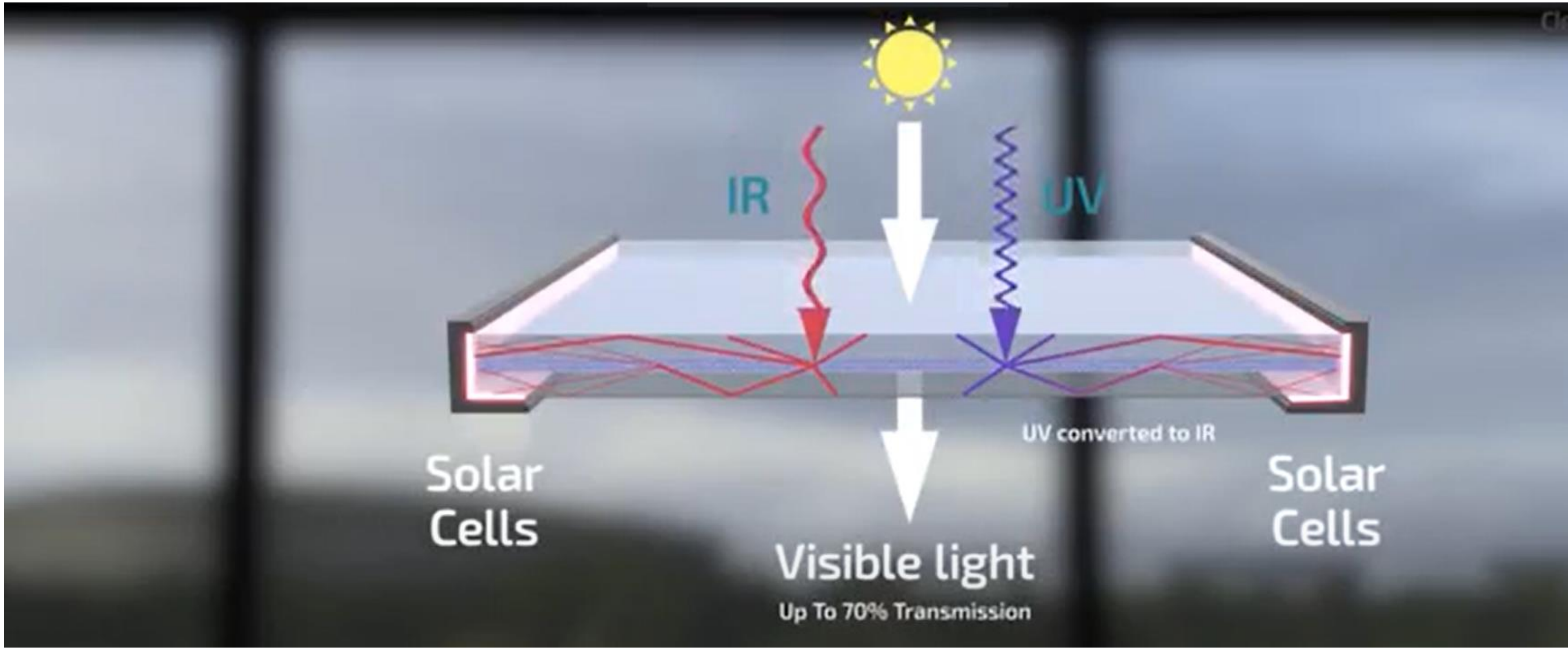
The required thermal cooling capacity can be determined on the basis of the number of passengers, the outside and inside temperatures in the vehicle and the door opening time.

By using modern heat pump technology, the electrical energy consumption can be reduced to about one third of the required cooling capacity.

Wave guiding can reduce the air conditioning output and generate energy at the same time

Beautiful, large panoramic windows, for example, no longer necessarily represent interiors that are too hot in summer or overloaded air conditioning systems. Rather, the surfaces can be equipped with wave-guiding glass, which reduces the amount of heat entering the vehicle, reduces the amount of energy used by the air conditioning system, and generates energy along the way. To name just one of the many optimization possibilities of the present.

In this way, the old-timers on Frankfurt's bridges are equipped on the outside with the aesthetics of the past and "on the inside" with the most modern technology of our time.



What does a mass balance look like?

Conclusion: The modular development strategy makes it possible to build up a large fleet of the most varied vehicle models with comparatively little effort.

On the Frankfurt bridges, comparatively few vehicles are needed for the required transport performance. Accordingly, more effort can be invested in the quality, durability and design per vehicle.

Externally, the bridge fleet consists of solitaires, both in the group of buses and trains and in that of passenger cars. Technically, however, modular development within these categories means that each vehicle does not have to be developed individually, but can be built modularly with only minor adaptations.

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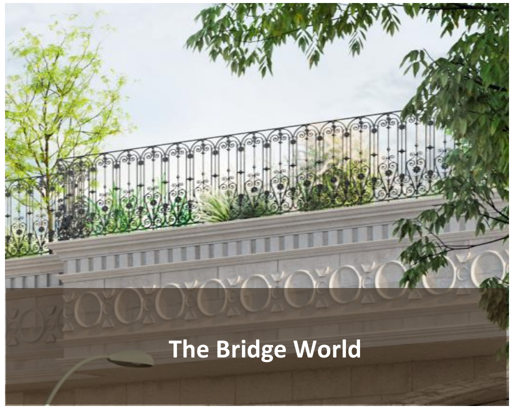
The Bridge World


Special quarters


Brückenvielfalt

CONTRIBUTING

Architecture	Geoinformation	Urban climate - global climate	Water	Law	**Critical sparring partners:**
Picture & Photo	Green & Nature	Statics	Packing	Finance	Professors
Bridges	Communication	Transport	Webpage & Design	Implementation	Professionals
Energy	Art & Culture	Technology & IT			Inspirers & Supporters

Logistics and Vision

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Aleksei Gorodenkov - alamy.de

A logistics simulation was carried out to determine the performance of the traffic system on the Frankfurt Bridges

The simulation of autonomously driving vehicles in the Frankfurt Bridge route network shows that 400 vehicles can transport around 40 million passengers per year with the help of the centrally controlled system. At the same time, most bridge routes are at least as fast as public transportation, often even faster. Above all, however, it is more convenient to travel from a bridge arm in the north across the ring to a bridge arm in the south (or from west to east) and neither have to change trains nor - especially at night or in the dark - have to descend into subway or commuter train shafts. Also taken into account in the simulation was the traffic of commercial vehicles (for multi-use system disposal, green maintenance, etc.).

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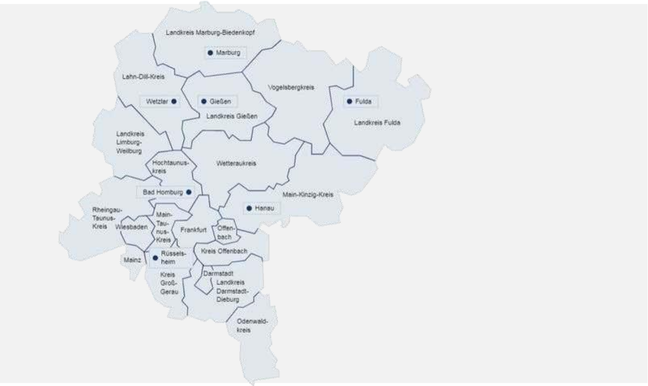
Basics and ACTUAL situation in Frankfurt am Main

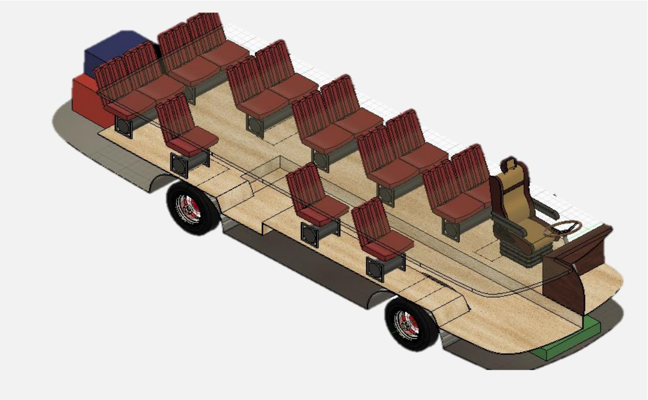


Persons transported by public transport in the Rhine-Main region

The initial situation in the city of Frankfurt am Main: The framework is provided by the passenger volume in the RMV area (route area of the Rhine-Main Transport Association), which extends from Darmstadt in the south via Frankfurt, Offenbach and Hanau to Marburg, Wetzlar and Giessen in the north and Fulda in the northwest. Around **788 million passengers** were transported there in 2018.

Persons transported by public transport in Frankfurt

The passenger volume specifically in the city of Frankfurt am Main: In 2019, Verkehrsgesellschaft Frankfurt am Main mbH (VGF) transported about 144 million passengers by subway and about 67 million people by streetcar. In addition, In-der-City-Bus GmbH (ICB) transports more than 31 million passengers per year by bus through Hesse's largest city. In total, therefore, around **242 million passengers** are transported within the city each year.



Persons transported by bridge means of transport

The overall system of Frankfurt bridges (BrückenNahVerkehr = BNV) can transport at least 70,000 people daily or at least 25 million passengers annually with its 200 trains and buses. Another 200 smaller vehicles can transport at least another 10 million passengers per year. With a passenger transport of at least 35 million passengers, the bridge traffic represents a significant relief for Frankfurt's road traffic.

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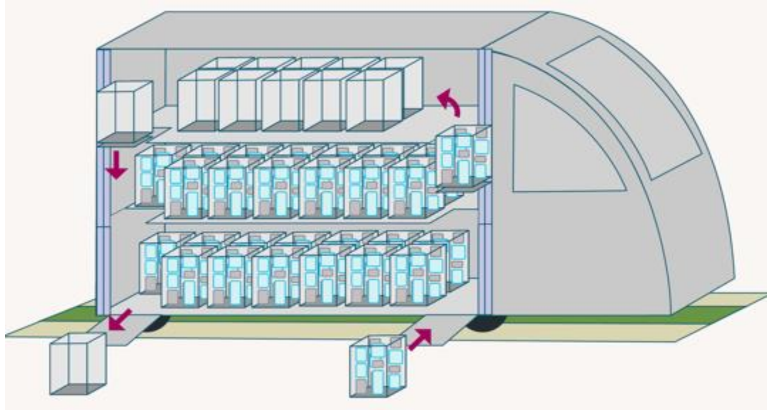
Over 400 trips per day were included in the simulation for the special vehicles - most of which are delivery trips

Police, fire and rescue service trips

In order to determine the number of trips made by the special vehicles that are attributable to the police and fire and rescue services, the statistics of the Frankfurt police headquarters with 114,421 calls per year and the data of the Frankfurt fire department with a total of 110,975 calls for fire and rescue services per year were used. These 225,000 calls served 763,380 residents of Frankfurt. Accordingly, for the 35,000 bridge residents, a maximum of 10,000 call-outs per year for police, fire and rescue services can be expected.

Trips for delivery traffic and mail

The same calculation system was used to determine annual parcel shipments. Throughout Germany, 3,650,000,000 CEP shipments (courier, express and parcel service shipments) are sent, which corresponds to about 45 deliveries per person per year. In addition, the delivery traffic for the businesses and stores on the bridges is taken into account with 1-2 deliveries per day for fresh products, whereby it was also included in the simulation that not every delivery comes from the same provider/supplier.



Trips to waste recycling

Normal residual waste is disposed of on the bridges by a pipeline system. Packaging waste hardly arises, as the purchases on the bridges themselves are collected separately in "renomats" with reusable packaging or PE packaging. For these, however, vehicles have to come to collect them, and more voluminous items such as green waste in particular (twigs, cut grass, etc.) also have to be taken away. Renomat collection is done at night with a total of approximately 15,000 collection trips per year. Green space waste and other hazardous waste was estimated at 5,000 trips p.a.

Basics and actual situation of hydrogen buses and trains in the BNV

Service life of H2 buses in the BNV

The number of H2 vehicles required was derived from existing transport systems with H2 buses. There, hydrogen buses have an availability of 0.6 with a daily service time of 8-16 hours and a 7-day per week operation. Therefore, the bridge vehicle requirement must be multiplied by at least 1.66 to get the real required amount of vehicles. With wider deployment of hydrogen technology, H2 vehicle fleet availability can be expected to increase to 0.85.

Downtime due to refueling and trips to service stations

In addition, all trips to refueling stations and the refueling time must also be taken into account. The bridge streetcars (i.e. vehicles with a train look) and buses are smaller than conventional H2 buses used in public transport. They are also significantly lighter in construction. The refueling time for vehicles of this size and weight is on average 10 minutes, so that about 2 refueling stops per vehicle per day are necessary.

Maintenance of a new technology

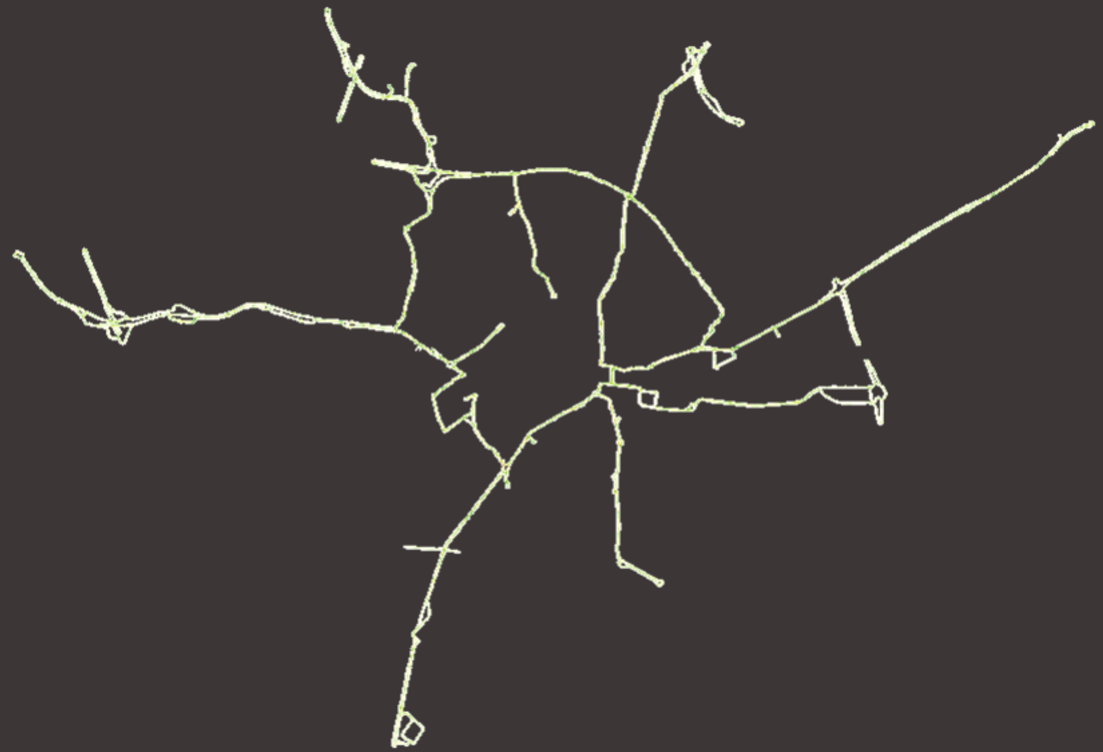
Hydrogen buses have a lower availability than buses with combustion engines. The biggest driver here is the maintenance interval, which is only 7 days for local passenger transport vehicles. With increasing use, further development and years of experience, it can be assumed that this maintenance interval can be reduced to the level of vehicles with internal combustion engines.

A logistics simulation was carried out to determine the performance of the transport system

The logistics simulation was used to determine the performance and maximum overall capacity of the transportation system.

In addition, based on the simulation results, an optimization of intersections, stations and route sections was carried out so that congestion and long waiting times can be avoided.

However, in the present simulation it was assumed extremely conservatively that the 200 larger vehicles stop at all stations. However, this is the absolute worst-case scenario, because the vehicles de facto only stop on demand at stations to which they come "on demand," i.e., when someone requests a vehicle there by pressing a button or has signaled their destination and location in advance by clicking on the bridge app.



300 vehicles transport people on the bridges over XY km through Frankfurt

The total route has a length of 60 kilometres, on which more than XY buses, cars and special vehicles transport passengers through Frankfurt around the clock. Table XY shows the number of vehicles available in the respective vehicle class.

Buses serve demand-driven, depending on the passenger demand in the bridge app, the stations on the route. Cars are used for private special trips and can also drive directly to entrances or parking lots of buildings - and therefore do not only stop at stations. In the category special vehicles are all vehicles that are necessary for everyday life on the bridges, such as garbage collection, fire department, police and post office.

Vehicle type	**Quantity [-]**	**Share of total fleet in %.**
Busses	100	23,25 %
Streetcars	100	23,25 %
Minibus (few station stops)	60	13,95 %
Car (no station stop)	140	32,55 %
Special vehicles	30	7 %
SUM	430	100 %

A logistics simulation was used to determine the performance and the maximum overall capacity of the traffic system. Furthermore, based on the simulation results, an optimization of intersections, stations and route sections can be carried out so that congestion and long waiting times can be avoided.

An average of around 40 million passengers per year can be transported on the Frankfurt bridges route network with a fleet of 400 vehicles to cover demand

The entire system with 266 stations, at which an average of 4 people get on or off (number of passenger changes), can thus transport at least up to 68,814 people to their desired destination every day. This is roughly equivalent to the population of the city of Fulda. If we assume a higher number of passenger changes of 6 or 7 people getting on or off the train, the number of people transported increases to around 100,000 to 120,000 per day. Calculated over the year, this means: 25 million people per year are transported on the Frankfurt bridges in the worst case scenario, but between 37 million and 44 million p.a. under normal conditions.

Half of the vehicle fleet consists of vehicles that can transport up to 25 passengers. In the best case, this means that at a station with a 90-second interval, up to 1,000 passengers are transported within an hour.

The illustrations below on the right show an example of the largest vehicle, a bus, which offers space for 16 seated passengers and provides for up to 10 standing passengers (the driver's seat including the steering wheel is not intended to control the autonomously driving vehicle, but results from the model of the vintage car replicas and is, for example, a particularly exciting seat for children).

Vehicle type	Seats	Standing room
Bus	15	10
CAR	2-4	0
Special vehicles (no passenger transport)	2	0
Streetcar (per wagon)	15	10

Performance promise instead of timetable: A short waiting time of 90 seconds enables fast routes to the desired destination

If the demand for buses is particularly high in one area of the route, stations there can be approached with a cycle time of up to 90 s, thus reducing waiting times for passengers to an absolute minimum. This is achieved by the demand-oriented on-demand system, the high number of vehicles available at any time, and route optimization by simulating extreme cases.

Vehicles that are not needed are cleaned and refuelled at the maintenance loops at the ends of the bridge arms, ready for a new deployment at any time.

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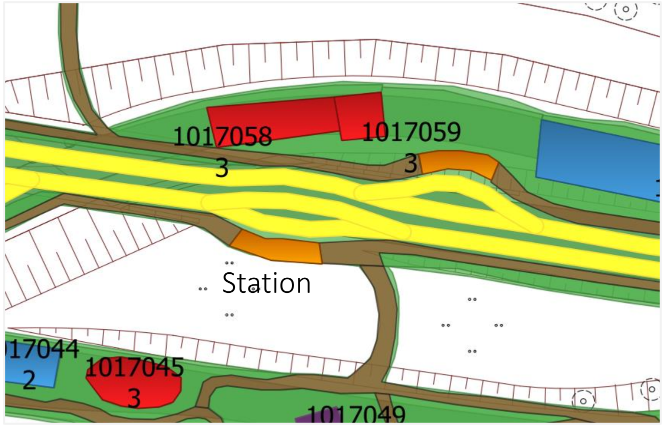
Procedure for route modeling and model building for simulation

Modeling of the route on city maps

To achieve the highest accuracy in the simulation, the route is modeled on city maps at a scale where one pixel corresponds to 0.169 meters. The route defines the direction of travel of the vehicles (opposite lane structurally separated) and specifies the route network on which the vehicles can move.



Modeling of the vehicles and stations

Vehicles are represented in the simulation as objects with defined length, acceleration, speed and many other parameters. Stations are represented as stop lines with a fixed position and a defined stopping time of the vehicles (which can also be specified statistically distributed).

Creation of the algorithm for controlling the Driving distance of the vehicles

The movement of the vehicles on the route network specified by the bridges is determined in the simulation by an algorithm that specifies parameters such as speed, acceleration, route to be traveled, stations approached, and the stopping time at stations.

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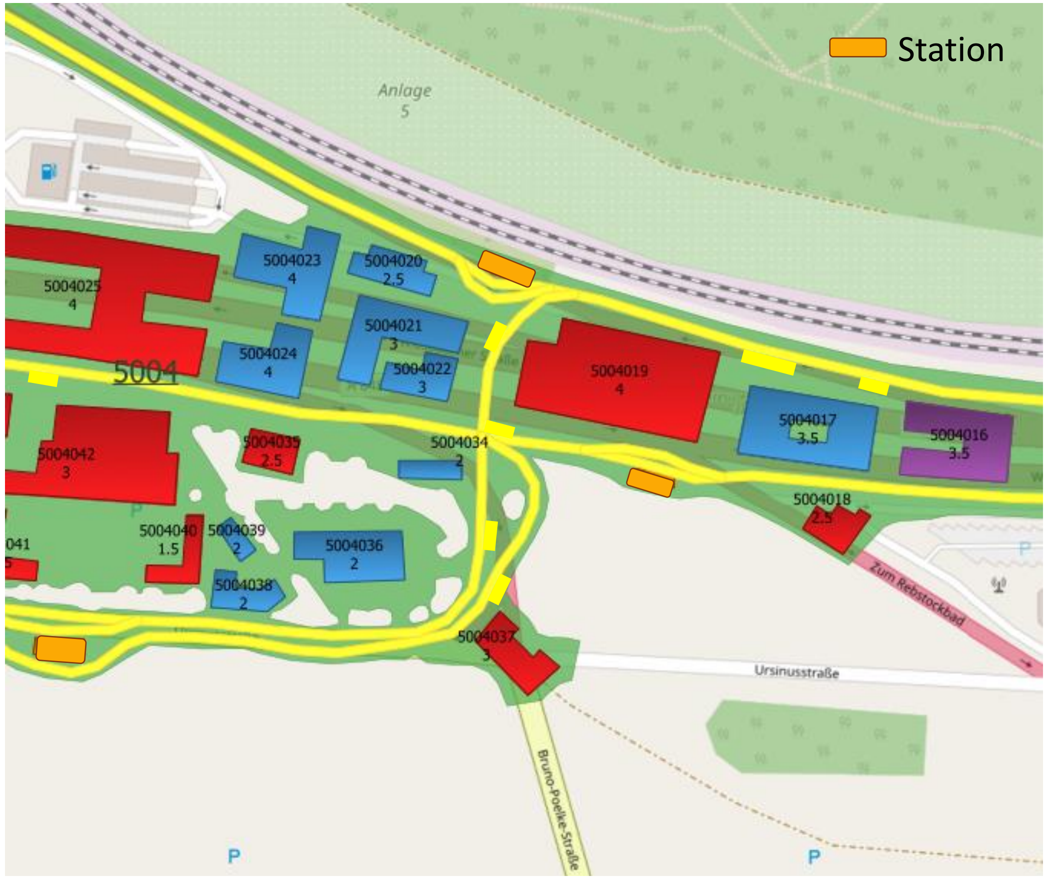
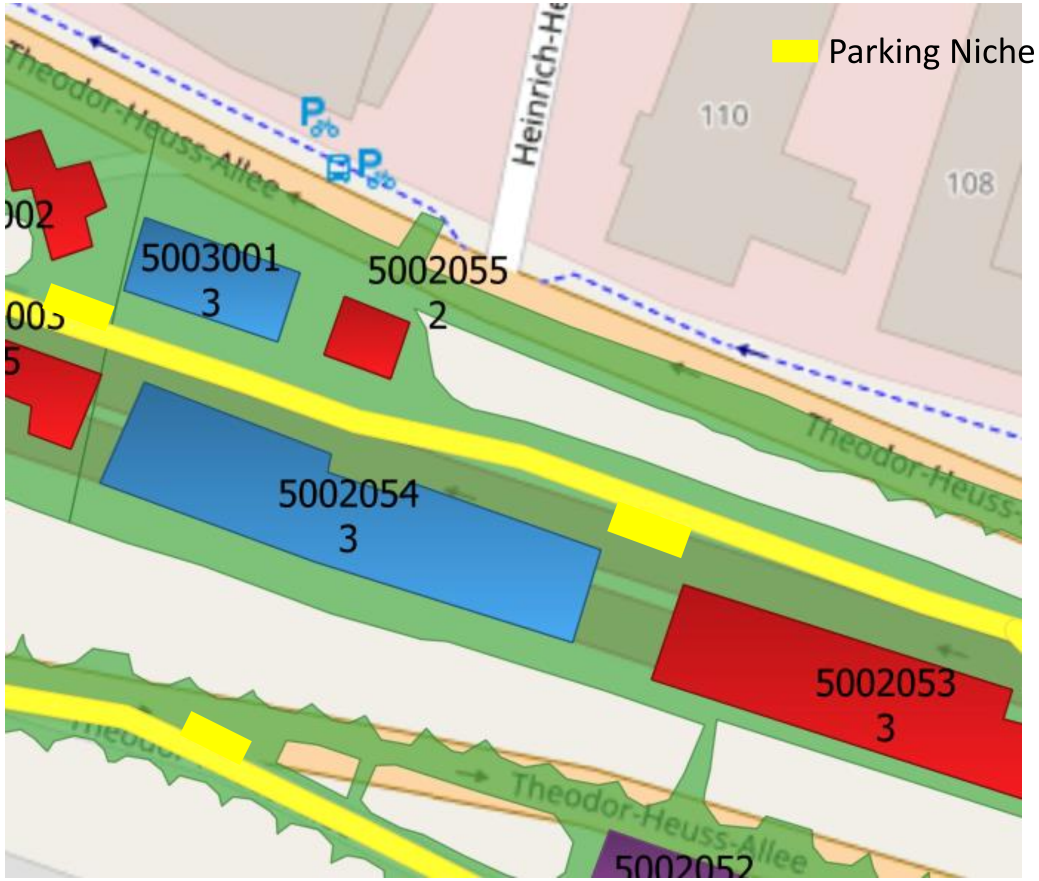
A large station network is being created on the Frankfurt bridges with numerous entry and exit points in Frankfurt

There are over 266 stations and 613 parking slots along the entire route. One station serves as a stop for the vehicles and at the same time as an alternative lane so as not to obstruct passing special vehicles such as the police, emergency medical services and fire department. In addition, they serve as a staging area for waiting passengers and enable barrier-free boarding and alighting. Parking niches, on the other hand, are used exclusively for parking cars and minibuses or for getting on or off at the destination.





The transport network of the Frankfurt bridges is divided into heavily frequented main stations and less frequented secondary stations

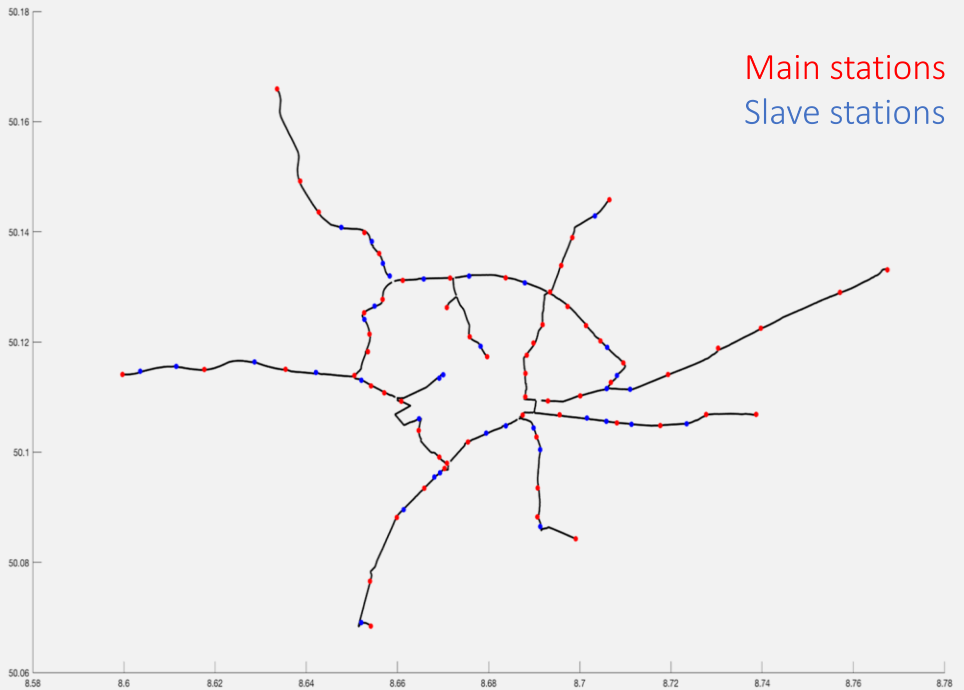
In the demand-responsive transit system, areas and stations with many trip requests are served much more frequently.

This results in main stations with very high demand, where approx. every 90 seconds, because the central system is informed (usually by cameras) about the high passenger volume; secondary stations, on the other hand, have a lower number of trip requests, which are usually also reported more frequently to the central control system via the bridge app and less frequently via cameras (anyone approaching a secondary station is more likely to enter their destination in advance via their bridge app, because they cannot assume that others are already waiting there and have "activated" the camera - at main stations, on the other hand, people tend to rely on the fact that vehicles are coming all the time anyway). This results in an average waiting time of 5 minutes until the next vehicle arrives at the secondary stations. The overview map in the figure shows this distribution with main stations in red and secondary stations in blue.

The main stations on the Frankfurt bridges are served by almost all vehicles.

Thus, the waiting time at these points is particularly short and, in the best case, is even only 50 seconds.

Main stations are often part of express routes, where only selected main stations are served to cover long distances quickly.



General transport strategy on the Frankfurt bridges

Circulating vehicles ensure supply to the stations within 50 seconds in the best-case scenario

In order to provide vehicles around the clock after only 50 seconds at stations in the best case, vehicles stop in all route sections to serve short-term demand. In other words, some vehicles circle in sections (especially on the ring road) without stopping at stations.

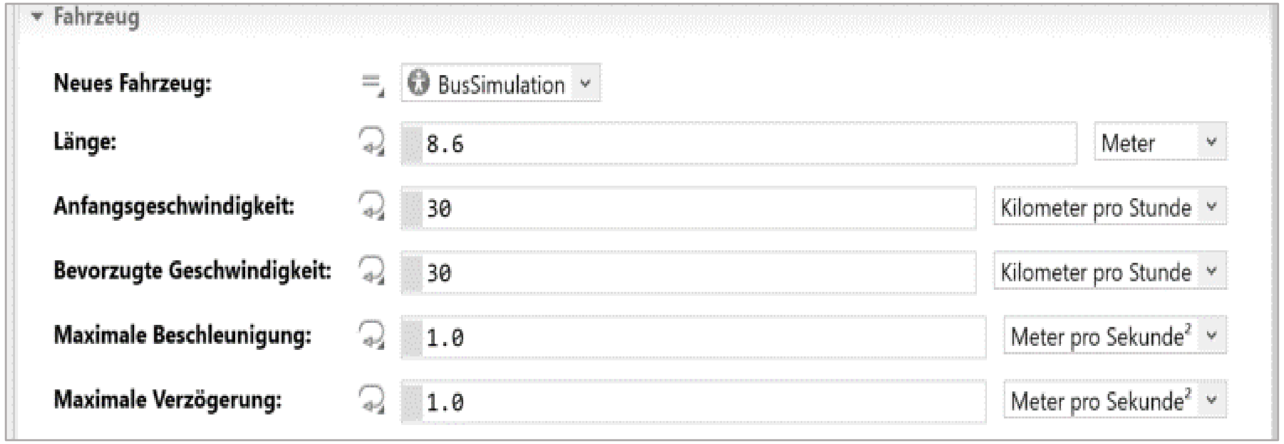
Private trips by car and minibus are carried out on demand - and all accessible vehicles always have priority in the overall system anyway

Thanks to the even distribution of parking bays across the route network, pickup is very fast even for last-minute requests. Accessible cars and "minibuses" always have priority over all other vehicles: they arrive the fastest.

Special vehicles only drive when required or on missions

Statistics from the city of Frankfurt and other major German cities were used to determine how many police, fire department, refuse collection and post office trips there are likely to be on the bridges on average. This was taken into account in the simulation as so-called "background noise", i.e. randomly circling vehicles. Emergency scenarios with absolute right-of-way for emergency vehicles have not yet been simulated as part of this feasibility study. A sufficient number of passing bays, on the other hand, was planned into the route.

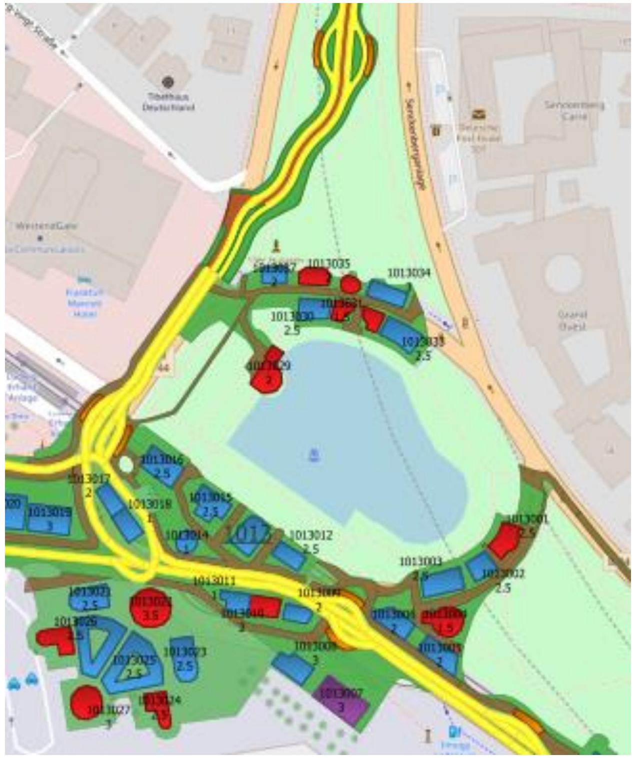
The logistics simulation was carried out with certain boundary conditions and input parameters



Parameterization of the vehicles

Vehicles were parameterized in the simulation as follows:

- Initial speed: 30 km/h
- Maximum speed: 30 km/h
- Positive acceleration: 1.0 m/s^2
- Negative acceleration: 1.0 m/s^2



Parameterization of the route

The route is parameterized as follows:

- The design of the curve radii was chosen in such a way that all sections can be driven at 30 km/h.
- No speed limits (maximum speed is limited to 30 km/h by the design of the autonomous vehicles).
- Turning vehicles allow passing vehicles to pass and turn only without obstructing following vehicles.

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For the simulation of stations and stops, among other things, empirical values from public transport were parameterized

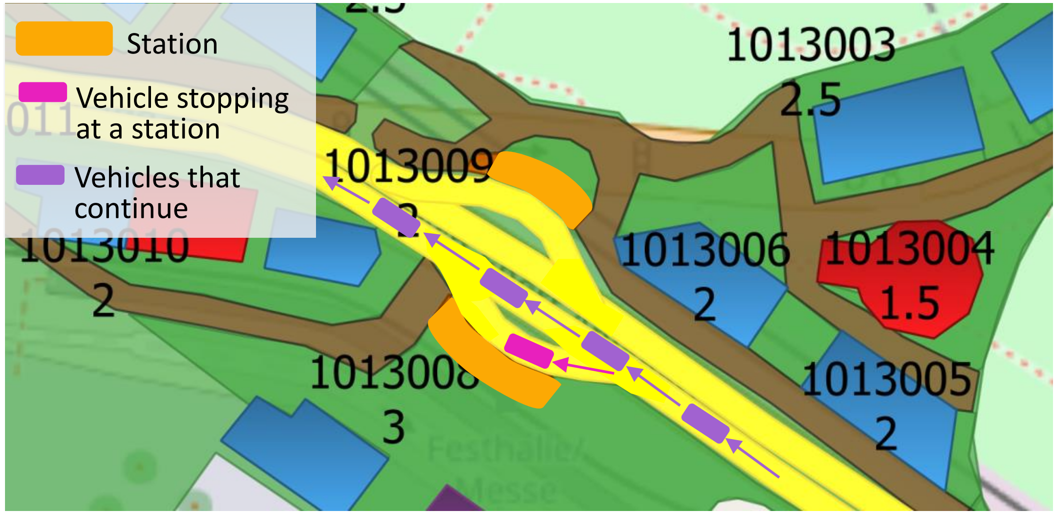
Stations are two-lane sections of track that have a stop line at a defined position where vehicles can stop to change passengers.

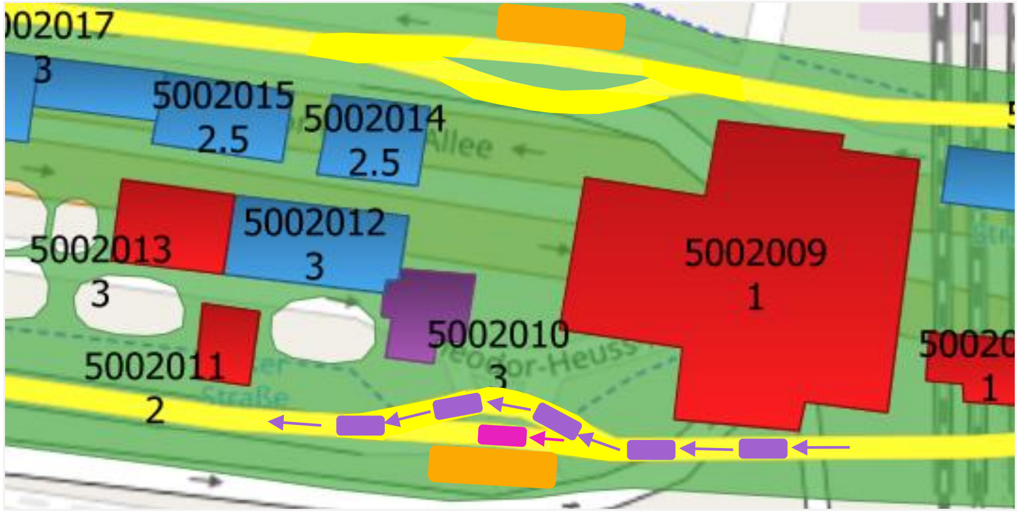
Vehicles that do not need to stop at the station can pass without obstruction in the second lane.

When entering stops, the vehicles decelerate to a standstill with the parameterized acceleration.

The vehicles then stand at the line for 30 seconds to allow passengers to board and alight. This value was determined empirically using a public transport system in a major Swiss city and used for the overall simulation.

Finally, the vehicles accelerate again with the parameterized value and rejoin the main line while observing the right-of-way rule.



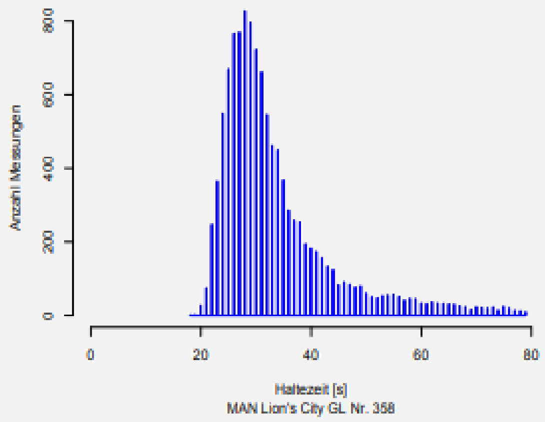


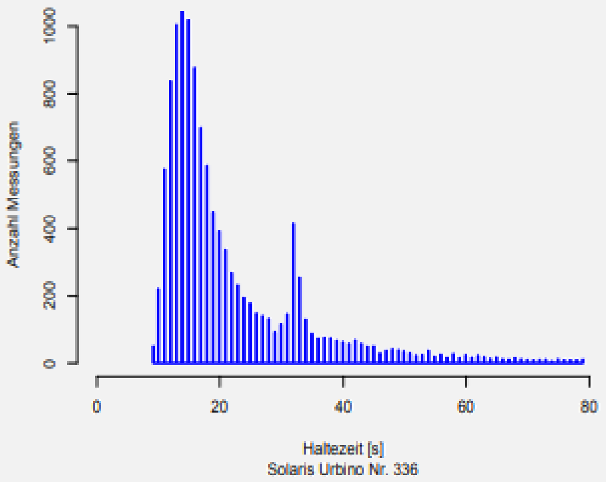
Reference research on average station stopping times in public transport

To define the input data and parameters into the logistics simulation, it is therefore necessary to use reliable data from the existing data of the public transport bus systems of major European cities.

The aim is to define the average duration of a stop at a station from the available data. This is made up of door opening and closing time, passenger changing time and the time until the vehicle restarts. This means that the complete period of time during which the vehicle is stationary is taken into account.

Parameter	Wert [s]	Source
Average holding time **(applied in simulation)**	30	Calculation based on master thesis Binswanger (City of Winterthur)
Maximum holding time	80	Value master thesis Binswanger
Maximum door opening and closing time	3	Design bridge buses and streetcars





Quelle: Daten vom Fahrgastzählsystem von Stadtbus Winterthur, ganztägig, 15.12.16-01.03.17, Linien 1, 5 und 7, Ausgabe in R

Additional information for the calculation of the average holding time

The histogram shows an all-day evaluation of a passenger counting system of the European city of Winterthur (CH). It becomes clear that a stop time of 80 seconds represents the worst case, since the majority -with over 75% of all stops- is shorter than 30 seconds.

Description of a simulation run of the logistics simulation for bridge traffic.

Scope of the overall simulation

- The supply of all stops on the entire modeled route network is simulated.
- Only one direction of travel is simulated, which is used by 50% of all existing vehicles.
- The aim of the simulation is to determine the performance of the system under maximum load.
- The simulation considers the worst case.

→ Simulation result

The simulation result is obtained from three measured key figures:

1. **Stop count**: Number of vehicles that stop at a station of the network within 24 hrs.
2. **Average speed**: The speed at which vehicles travel on average.
3. **Total time**: The time required by the vehicles to travel to a sequence of stops.

Description of a simulation run of the logistics simulation: The algorithm for the route of the vehicles in the system works with fixed values

Generation of the vehicles

At the beginning of the side arms, vehicles are created with a time interval of 90 seconds from a so-called "source" (this "creates" vehicles that start anew in the route network).

The vehicles then stop at all stations on this side arm - this is the worst case: in reality, they only stop at stops for which demand has been reported to the central control system.

Operation of the entire route network

The vehicles drive along the ring road and other side arms according to the following system:

– The vehicles travel via the ring to *all* other side arms: All stations are served both on the ring and on the side arms. The distribution of how many vehicles call at which side arms is determined as follows:

Route section	Number of vehicles [-]	Percentage share [%]
Ring total	85	25,00%
Offenbach side arm	16	4,64%
Side arm Darmstädter Landstraße	12	3,48%
Kennedyallee side arm	38	11,15%
Side arm Theodor-Heuss-Allee	65	19,04%
Side arm Rosa Luxemburg / Nidda	41	12,08%
Side arm Friedberger Landstraße	27	7,90%
Side arm Hanauer Landstraße	46	13,47%
Inner arm Kurt-Schumacher Street	6	1,76%
Side arm Eschersheimer Landstraße	5	1,47%
Background noise (special vehicles etc.)	60	n.a.
SUM	**400**	**100%**

– Not only are all side arms served, but also the ring is completely served with one line.
– Vehicles of the so-called "basic noise" travel the ring without stopping at stations.
– Since only one direction of travel was considered in the simulation, all vehicle counts were used halved.
– A total of 74 lines from each branch serve all areas and stations of the route network.

Simulation run

Once all 400 vehicles have been brought into the system via the sources and distributed to the lines according to the key shown in the table, they repeat their route until the end of the simulation (predefined simulation time: 86,000s = 24h).

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A logistics simulation run can be divided into three stages

Start of the simulation

From the start of each simulation run, vehicles are generated at the starting point of each side arm as well as at a point in the ring with a time interval of 90 seconds from a so-called source (this generates vehicles that start anew in the route network - see above).

Course of the simulation

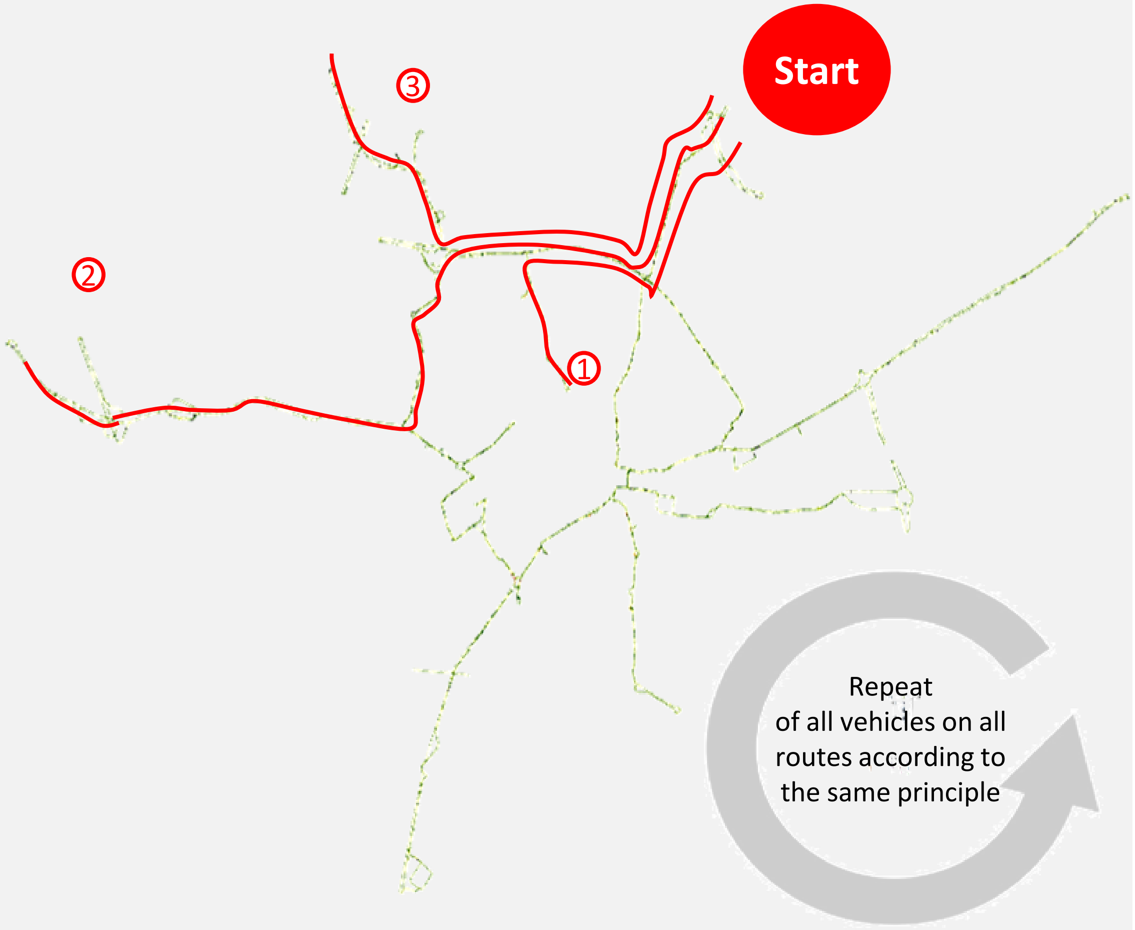
Once all vehicles have started into the route network (340 vehicles stopping at stations and 60 vehicles representing the background noise), they travel to all areas of the route network according to the distribution key described on the previous page.

When a vehicle reaches the end of its route, the vehicle repeatedly travels along this route. This ensures that the defined distribution key is adhered to throughout the simulation run - and that each route section is served continuously.

End of simulation

A simulation run for the traffic on the Frankfurt bridges ends after 86,400 s, which corresponds to a simulation time of 24 hours. At this point, the statistics are stored and evaluated.

Each simulation run of the logistics simulation follows an algorithm that assumes certain routes of the vehicles



Simulation process - graphically explained

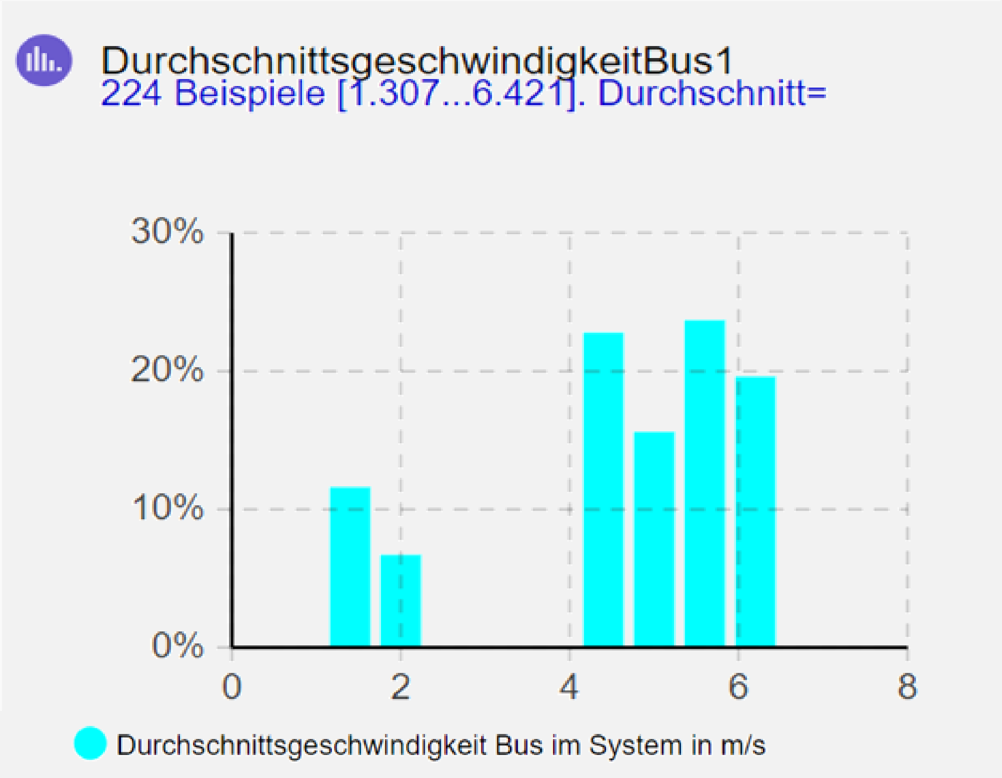
The vehicles start at the beginning of a side arm, then drive through all stations of this side arm and then distribute themselves according to the distribution key in the system.

I.e. there is a line that travels from the start side arm onto the ring and then into the nearest side arm (1), then a line that travels after the start arm into the side arm after the next (2) and one that travels along the third arm from the start side arm (3). Once a vehicle has completed the route, it travels along it again.

For clarity, the figure shows this as an example for one sidearm as well as only for the subsequent distribution into 3 sidearms/areas of the system.
In total, all other side arms and the ring are traveled from each side arm. Including background noise, this results in 74 lines.

The simulation result shows: Local bridge traffic provides a high-performance and reliable transportation promise, as simulated key figures show

To ensure that the performance promise is met even before the line is built, a wide variety of key performance indicators are used in the logistics simulation - which are measured during each simulation run:
Number of vehicles - Cycle time - Stops per vehicle - Stops per stop - Total travel time of a vehicle - Distance traveled by a vehicle, etc.



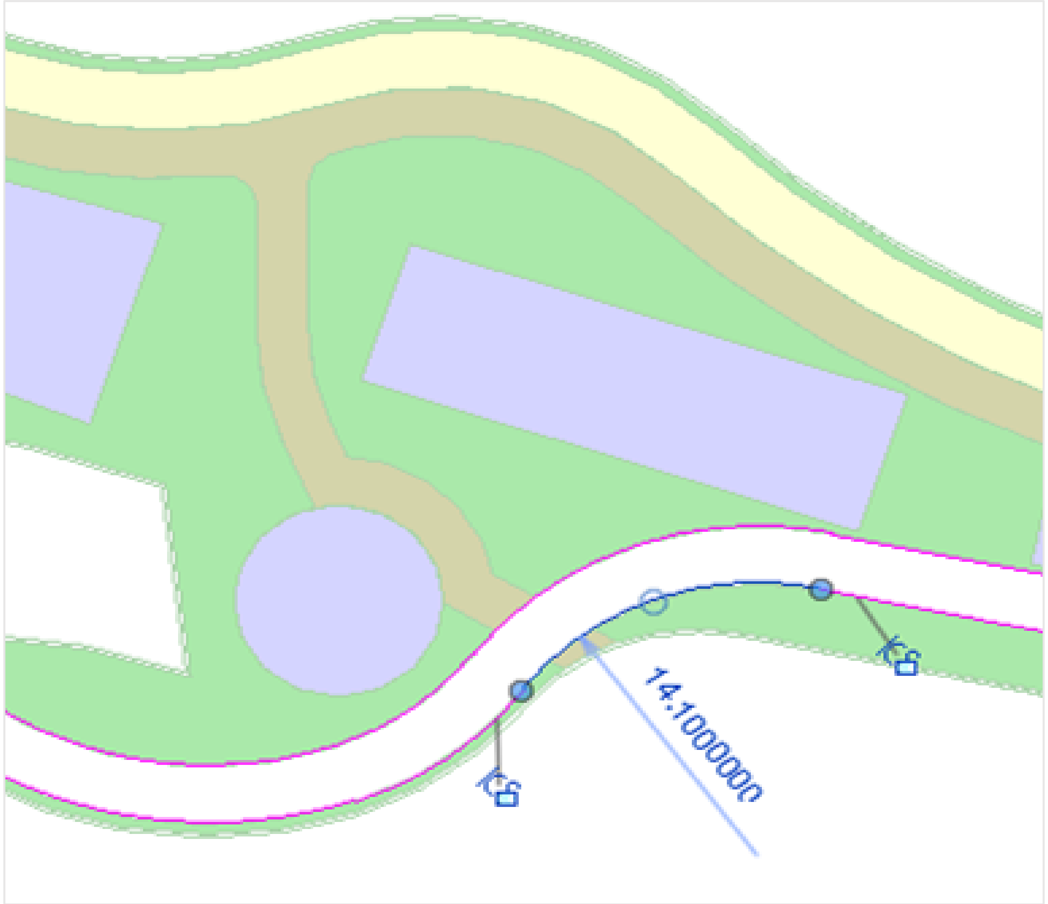
Vehicles on the bridges travel at an average speed of around 19 km/h

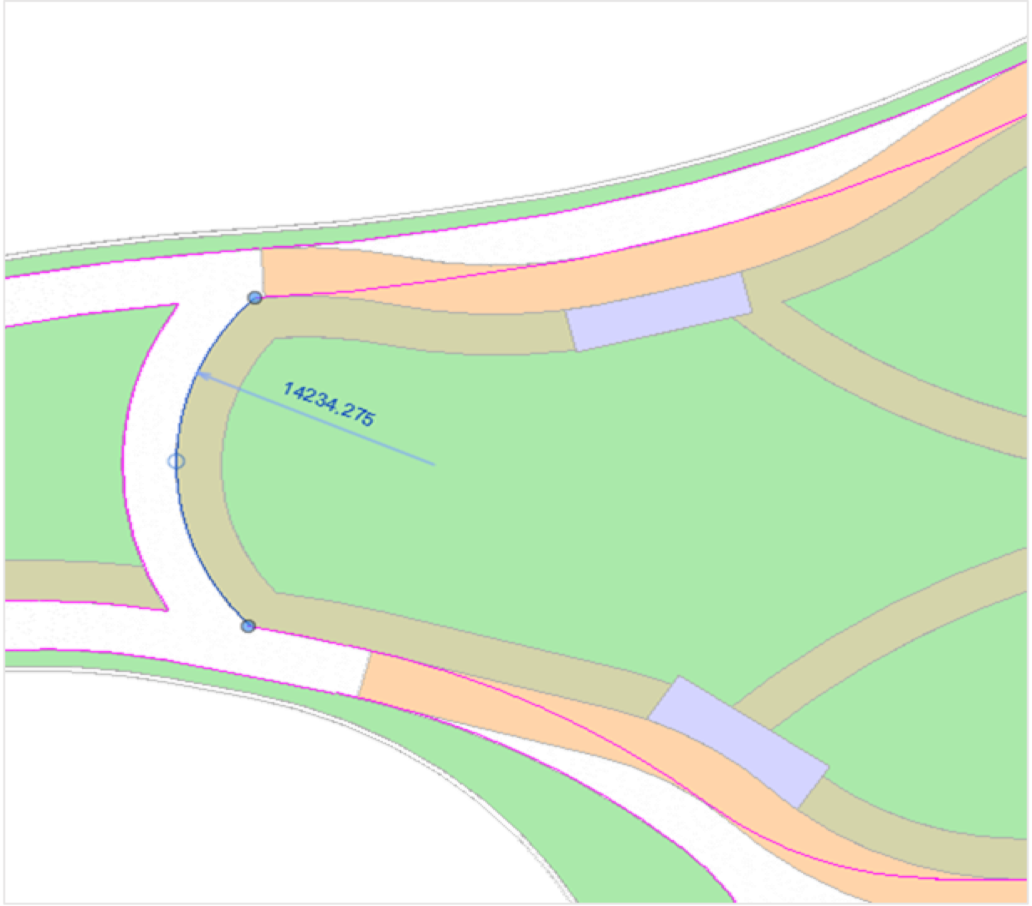
Deceleration and acceleration before and after stops were included in the average speed - the stopping time, however, was not included in this average value.

Away from the stop and station areas, vehicles travel at 30 km/h unless they brake at passenger crossings. However, these travel interruptions were not taken into account in the simulation, as they would have gone beyond the scope of the feasibility study.

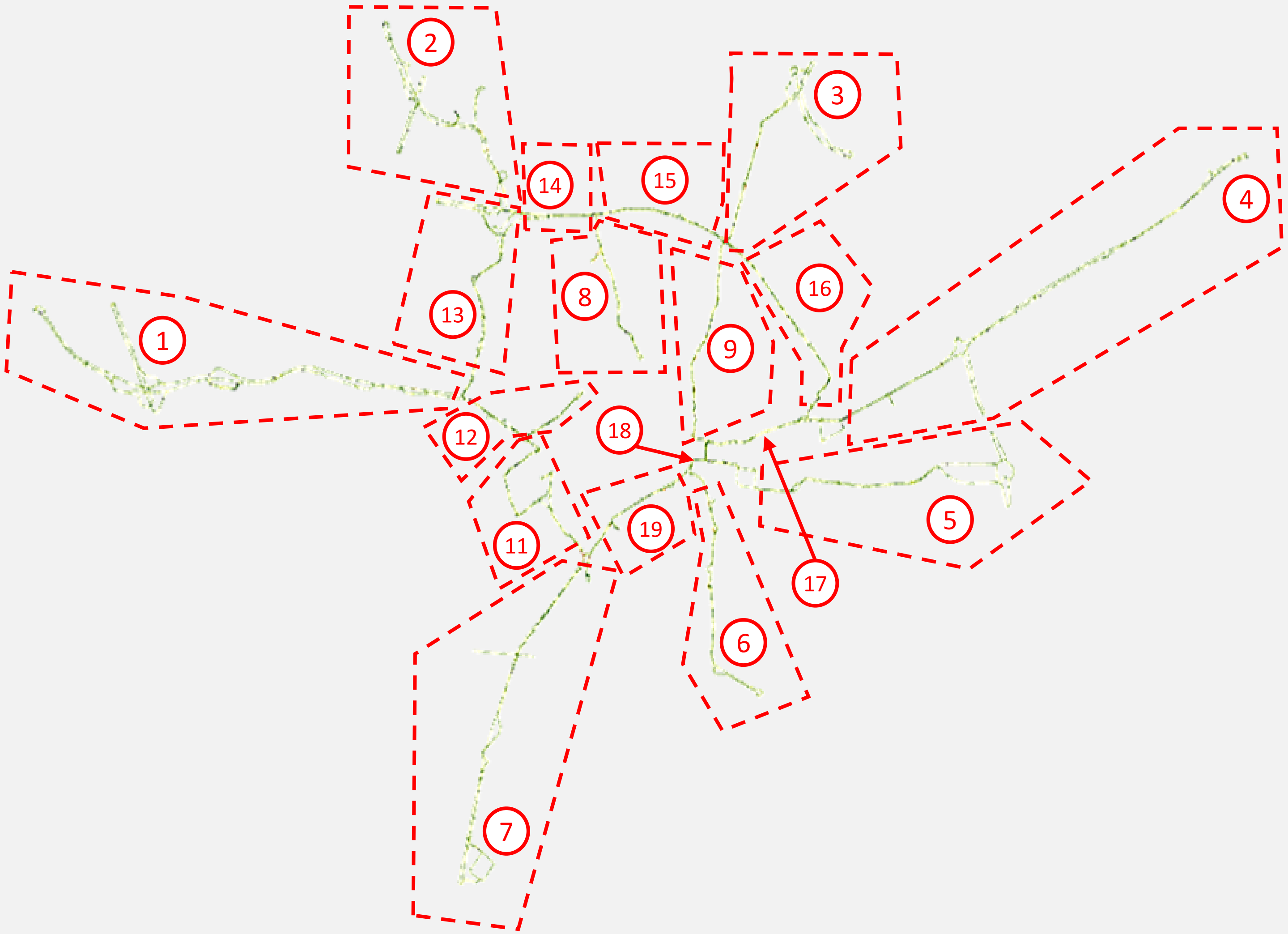
Speed affects passenger comfort: This was taken into account in the route planning, as were the short transport times

The speed at which a vehicle can negotiate a curve is determined by the geometry of the track and the specified limits for lateral acceleration. For traffic on the Frankfurt bridges, the lateral acceleration is set at a maximum of 1 m/s^2 , which allows passengers to move safely in the vehicle during the journey and also to enjoy the ride while standing. This was taken into account in the route planning by means of large curve radii, allowing the vehicles to negotiate almost all curves at 30 km/h.





The bridge traffic system (BVS) was divided into different sections



Result of the simulation: At least about 70,000 passengers can be transported daily with the larger vehicles on the bridges, in total at least 25 million per year - if the parameter "passenger change at stations" is increased from four to 6 to 7, at least about 40 million passengers can be transported annually.

The final result of the overall simulation can be output by sections of the traffic system and includes the following quantities:

- Number of stops per section in 24 h.
- Average cycle time per section over 24 h.
- Passengers transported per section in 24 h, assuming an average of 4 passenger changes per stop (e.g., 2 boardings and alightings each).

	SN1-TheodorHeuss	SN2-Nidda	SN3-Friedberg	SN4 - Hanau	SN5 - Offenbach	SN6 - Darmstädter	SN7 - Kennedy	SN8 - Eschersheimer
Stops at stops /24h	1.029	470	293	394	402	314	492	773
Persons transported / 24h	4.116	1.880	1.172	1.576	1.608	1.256	1.968	3.092
Cycle time (average 24 h)	84	184	295	219	215	275	176	112

	SN9 - Kurt Schumacher	Ring part 11	Ring part 12	Ring part 13	Ring part 14	Ring part 15	Ring part 16	Ring part 17	Ring part 18	Ring part 19
Stops at stops /24h	303	1.451	1.451	1.484	1.725	1.282	1.125	1.324	1.472	1.420
Persons transported / 24h	1.210	5.804	5.804	5.936	6.900	5.128	4.500	5.296	5.888	5.680
Cycle time (average 24 h)	286	60	60	58	50	67	77	65	59	61

According to the simulation (in the worst case scenario), a total of 68,814 people are transported per day (25.1 million passengers per year).

The fastest cycle time is 50 seconds. The slowest cycle time is 295 seconds (4 minutes 55 seconds).

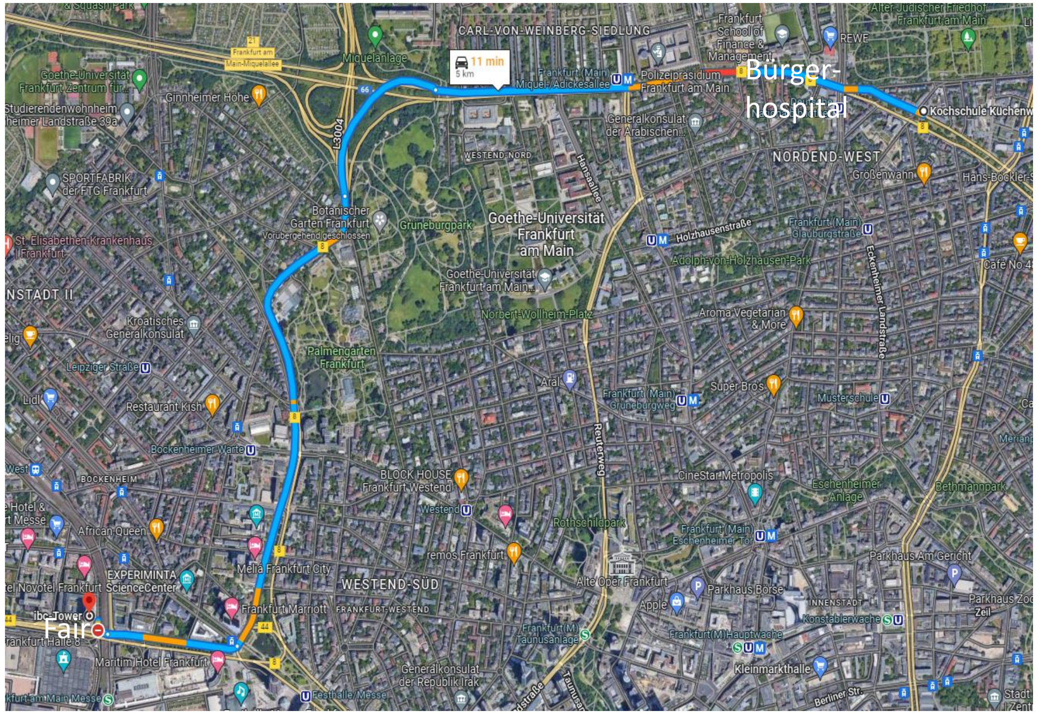
Route examples show that bridge vehicles along the ring connect many points faster than RMV - despite low average speed of around 19km/h

Example 1: With bridge transport, it takes 21 minutes to get from Bürgerhospital in Bornheim to the trade fair entrance near Emser Brücke - with RMV, on the other hand, it takes 25 minutes plus potential waiting time at the station of up to 15 minutes and a total walk of 11 minutes.

When the road is free and there is no traffic jam, cars on the road are of course the fastest - they can be surpassed by bridge traffic only by pleasant driving experience, high safety and convenience (you do not need to drive yourself and park your vehicle, refuel it, etc.).

Means of transport	Duration of the trip [min]	Number of transfers
Bridge vehicle	21 min	0
Road car	11 min	0
RMV	25 min	0 (plus 11 minutes walk)

Data for RMV and road passenger cars from Google Maps, on 18.11.2022 between 15:30 and 16:15 hrs.



For many point-to-point connections along the bridge ring, public transport is only slightly slower, but its use requires changing trains, whereas with local bridge transport (BNV) one can comfortably drive through

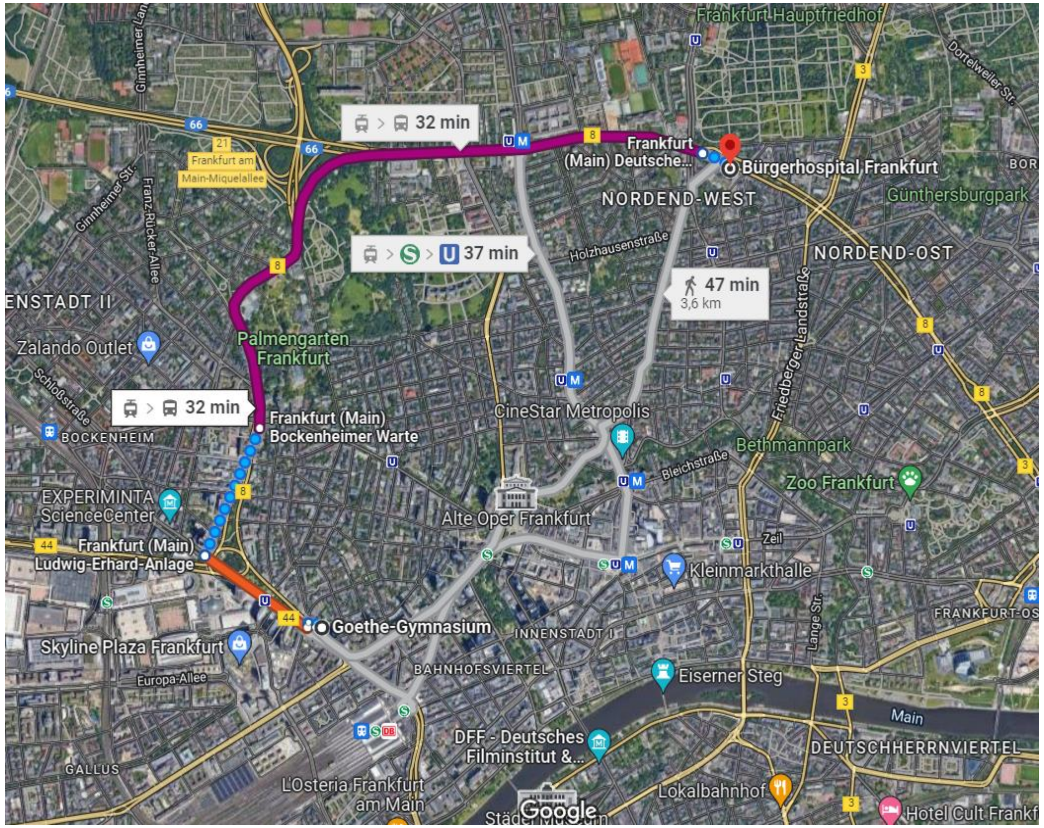
Addition to route example 1: in 23 min from Bürgerhospital to Goethe-Gymnasium. If you live in Bornheim today and want to send your child to the Goethe-Gymnasium at Friedrich-Ebert-Anlage, you have to put up with having to travel parts of the route twice above ground or once subway by S-Bahn or U-Bahn. With the BNV, on the other hand, all schools along the ring (about a dozen secondary schools and also numerous elementary schools) can be reached more easily for many Frankfurt residents who live on the other side of the city and often do not even consider these schools for their children because of more costly public transport connections.

Means of transport	Duration of the trip [min]	Number of transfers
Bridge vehicle	23 min	0
Road car	17 min	0
RMV	32 min	1

07:43 (Montag) bis 08:15 32 min
17 > M32
07:45 ab Frankfurt (Main) Hohenstaufenstraße
14 min
Details

⚠ 07:40 (Montag) bis 08:17 37 min
17 > S5 > U1 >

08:13 (Montag) bis 08:45 32 min
17 > M32



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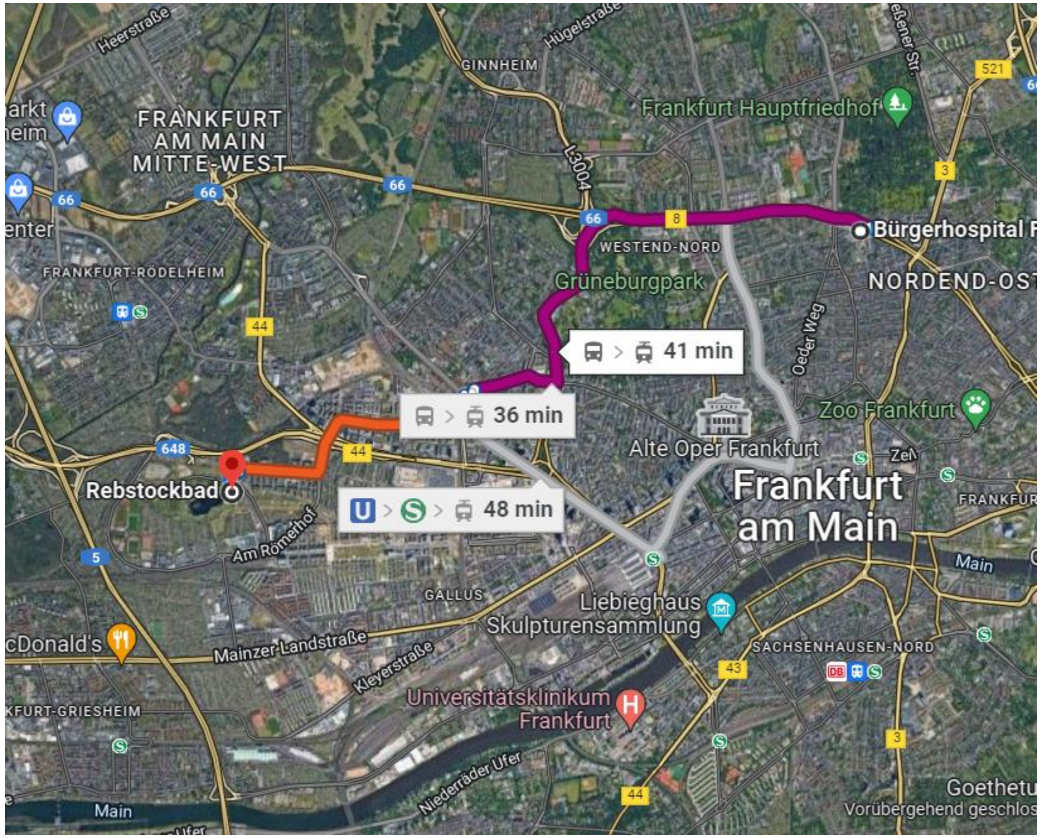
Leisure facilities in the city can also be reached much more easily and comfortably with the BNV: Both the facilities in the city center are easily accessible for residents on the outer arms of the bridges with the BNV, as well as facilities on the "other side" of the city.

Route example 2: From Bornheim to Rebstockbad in 33 minutes without changing trains - by public transport, the journey takes the same amount of time, but you have to change trains at least once. If you travel even further from the east to Rebstockbad, e.g. from Helmholtzschule, the journey time by public transport increases to 42 minutes, or you have to change to the subway once for a faster connection - local bridge transport, on the other hand, takes only a few minutes more and runs "door to door" over days.

Means of transport	Duration of the trip [min]	Number of transfers
Bridge vehicle	33 min	0
Road car	27 min	0
RMV	36 min	1

Bus & Bahn - Montag, 16.01.23

Bahnhof / Haltestelle	Zeit (früher | Erste Fahrt)	Dauer	Umst.	mit
Frankfurt (Main) Richard-Wagner-Straße – Frankfurt (Main) Rebstockbad	16:35 ab 17:05 an	0:33	1	
Frankfurt (Main) Deutsche Nationalbibliothek – Frankfurt (Main) Rebstockbad	16:38 ab 17:05 an	0:31	1	
Frankfurt (Main) Deutsche Nationalbibliothek – Frankfurt (Main) Rebstockbad	16:42 ab 17:13 an	0:35	2	
Frankfurt (Main) Richard-Wagner-Straße – Frankfurt (Main) Rebstockbad	16:45 ab 17:20 an	0:38	1	
Frankfurt (Main) Deutsche Nationalbibliothek – Frankfurt (Main) Rebstockbad	16:48 ab 17:20 an	0:36	1	



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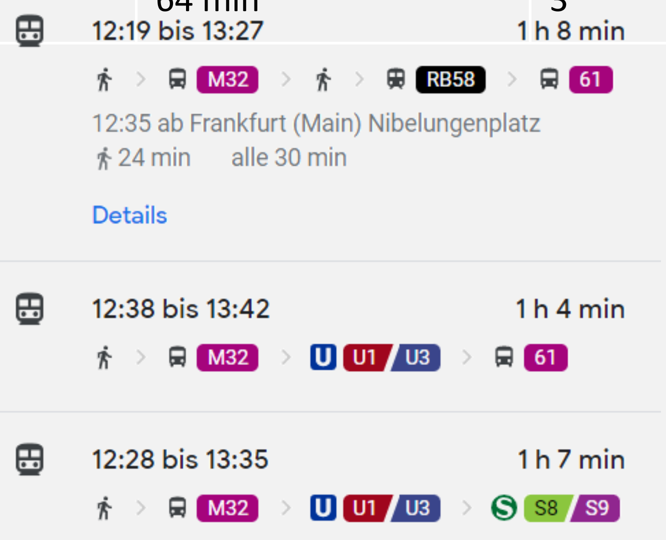
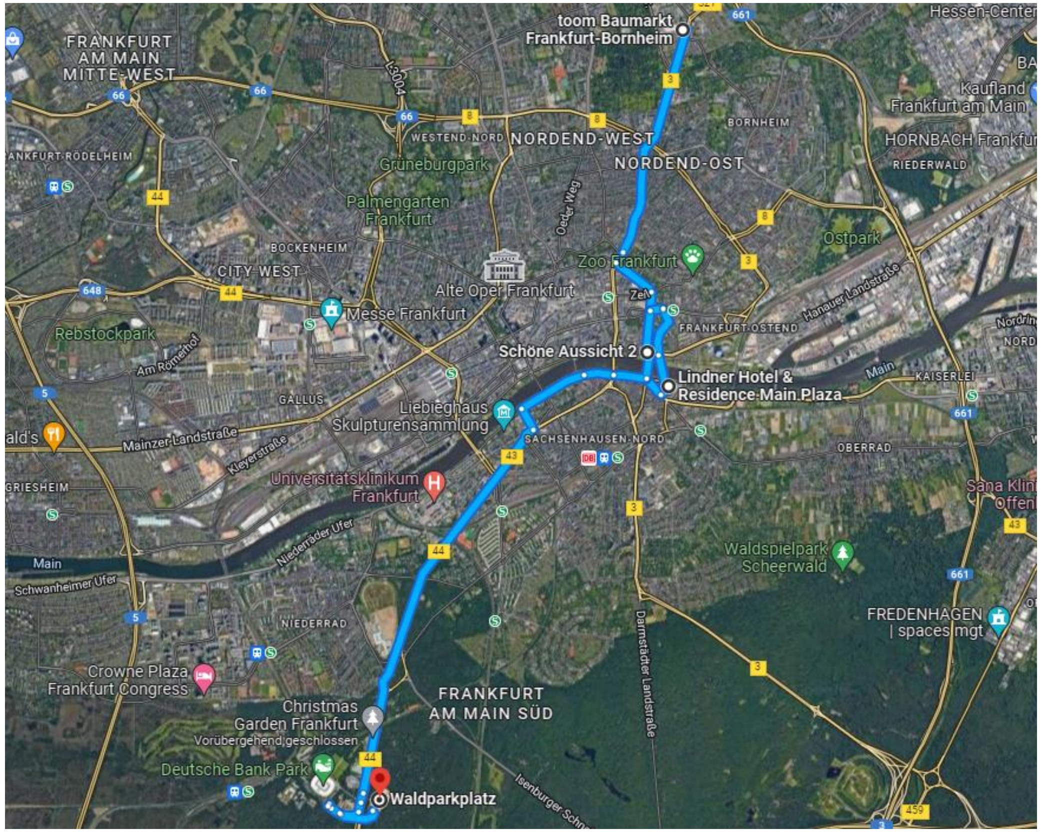
You can get from one outer arm of the Frankfurt bridges to the other outer arm by BNV in almost half the time as by public transport - and even the journey on the roads by car is no longer significantly faster on these routes

Route example 3: From Bornheim to Deutsche Bank Park (formerly Commerzbank Arena) takes only 37 minutes by BNV, but more than an hour by public transport - with three changes and (in the case of the fastest connection) with a partial journey in the subway - which is less pleasant for children, women or elderly people than using transport "above ground", especially in the evening and night hours.

Means of transport	Duration of the trip [min]	Number of transfers
Bridge vehicle	37 min	0
Road car	31 min	0
RMV	64 min	3





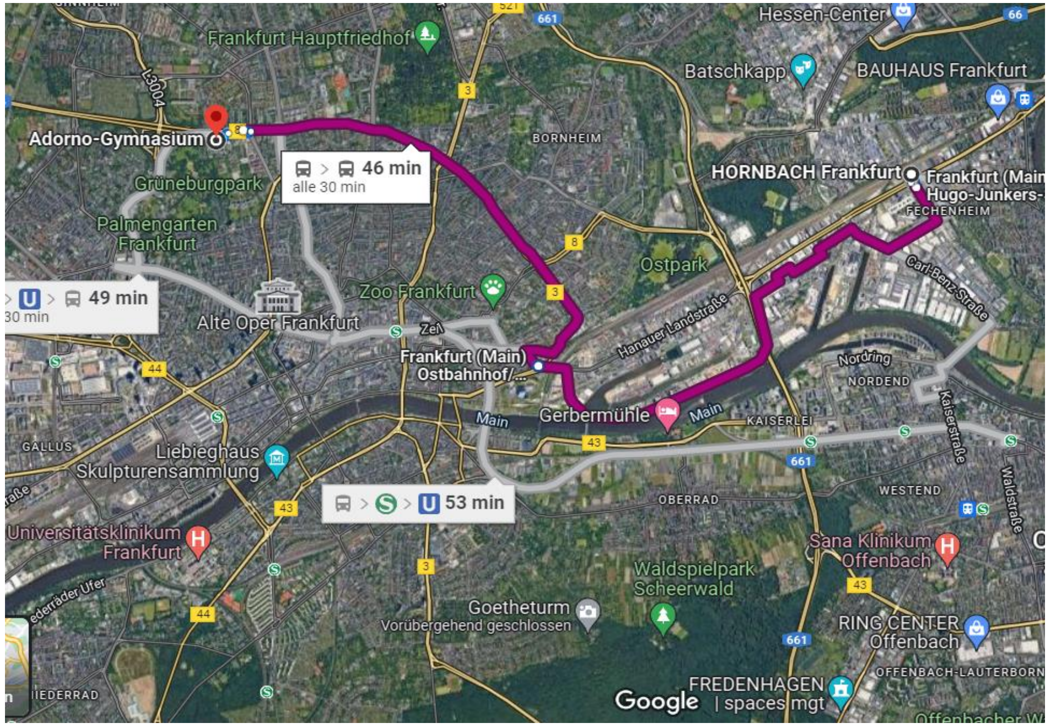
There are also routes on which local bridge transport is significantly slower than public transport - but still with the advantage that even unusual connections can be covered without changing trains

Example 4: If you want to get from Fechenheim to the Carl-von-Weinberg-Siedlung at Miquelallee, you can do it by public transport in three quarters of an hour, while the local public transport takes (worst case) more than an hour - assuming, as in the simulation, that the vehicle stops at almost all stations along the way. However, if we assume that in reality there will also be trips with few station stops, the trip duration of the BNV comes close to that of the ÖPNV.

The respective situations or circumstances on the route also change the results of a speed comparison for passenger cars on the road: In the event of a traffic jam on Hanauer Landstraße, for example, the trip from Fechenheim to Miquelallee by passenger car on some days can also lead to completely different values than the average of 20 to 40 minutes mentioned here.

Means of transport	Duration of the trip [min]	Number of transfers
Bridge vehicle	73	0
Road car	20-40 min	0
RMV	46 min	3 plus longer footpaths

Bahnhof / Haltestelle	Zeit früher | Erste Fahrt	Dauer	Umst.	mit
Bus & Bahn - Montag, 16.01.23				
Frankfurt (Main) Hugo-Junkers-Straße Frankfurt (Main) Miquel-/Adickesallee	12:21 ab 12:55 an	0:48	2	
Frankfurt (Main) Hugo-Junkers-Straße Frankfurt (Main) Grüneburgpark	12:27 ab 13:02 an	0:43	1	
Frankfurt (Main) Hugo-Junkers-Straße Frankfurt (Main) Miquel-/Adickesallee	12:35 ab 13:05 an	0:44	2	
Frankfurt (Main) Hugo-Junkers-Straße Frankfurt (Main) Grüneburgpark	12:35 ab 13:12 an	0:45	1	



The fastest traffic route through Frankfurt on average are the bridges

As the table below shows, the bridge network is one of the fastest ways to get around the Frankfurt metropolitan area. Particularly in comparison to the existing RMV public transport services, the vehicles on the bridges are an attractive alternative to reach the respective desired destination - a relief for road traffic as well as for public transport.

Route	Means of transport	Travel time [min]	Number of transfers	Percentage deviation
Route example 1	Bridge bus	21 min	0	0
Route example 1	Road car	11 min	0	- 48 %
Route example 1	RMV	25 min	0 (footpath necessary)	+ 15 %
Route example 2	Bridge Bus	33 min	0	0
Route example 2	Road car	27 min	0	- 17 %
Route example 2	RMV	59 min	1	+ 81 %
Route example 3	Bridge bus	37 min		0
Route example 3	Road car	31 min	0	-16 %
Route example 3	RMV	68 min	3 (long walking distances necessary)	+ 84 %
Route example 4	Bridge bus	73 min	0	0
Route example 4	Road car	30 min	0	-59 %
Route example 4	RMV	46 min	4 (several footpaths)	-37 %

The present simulation has considerable optimization potential because it assumes the worst case of the load on the overall system: For real operation, a significantly better performance of the traffic system can be expected in the "normal case" - which means that significantly more than 25 million passengers p.a. can be transported.

The present overall simulation simulates the extreme case / worst case of the load on the overall system. In real operation, there is a "normal operation" compared to this worst-case load, with a significantly higher performance of the traffic system:

1. In real operation, stations are approached on demand (passenger requests ride via app or camera reports that someone is waiting at the station, who may have entered their destination on a screen there) - i.e. unlike in the worst-case load simulation, stops are no longer made at every station, but only where people are also boarding or alighting.
   → Reduction of the time required for the distance traveled, since deceleration, 30 s stopping time and acceleration at all skipped stations are eliminated.

2. Areas where there is no or low demand can also be served less frequently or only on request, because passengers can book rides as needed via app (even in advance or already on the way to the stop). This creates capacity for areas with high utilization.
   → Reduction of the cycle time in rush hour traffic
   → Increase in the maximum number of passengers that can be transported in rush-hour traffic.

3. if necessary, the number of vehicles can be increased to some extent (by postponing routine maintenance stops at the bridge ends) to reduce cycle times and increase the number of people carried.
   → Reduction of the cycle time of all sections
   → Increase in the maximum number of people that can be transported in all sections.

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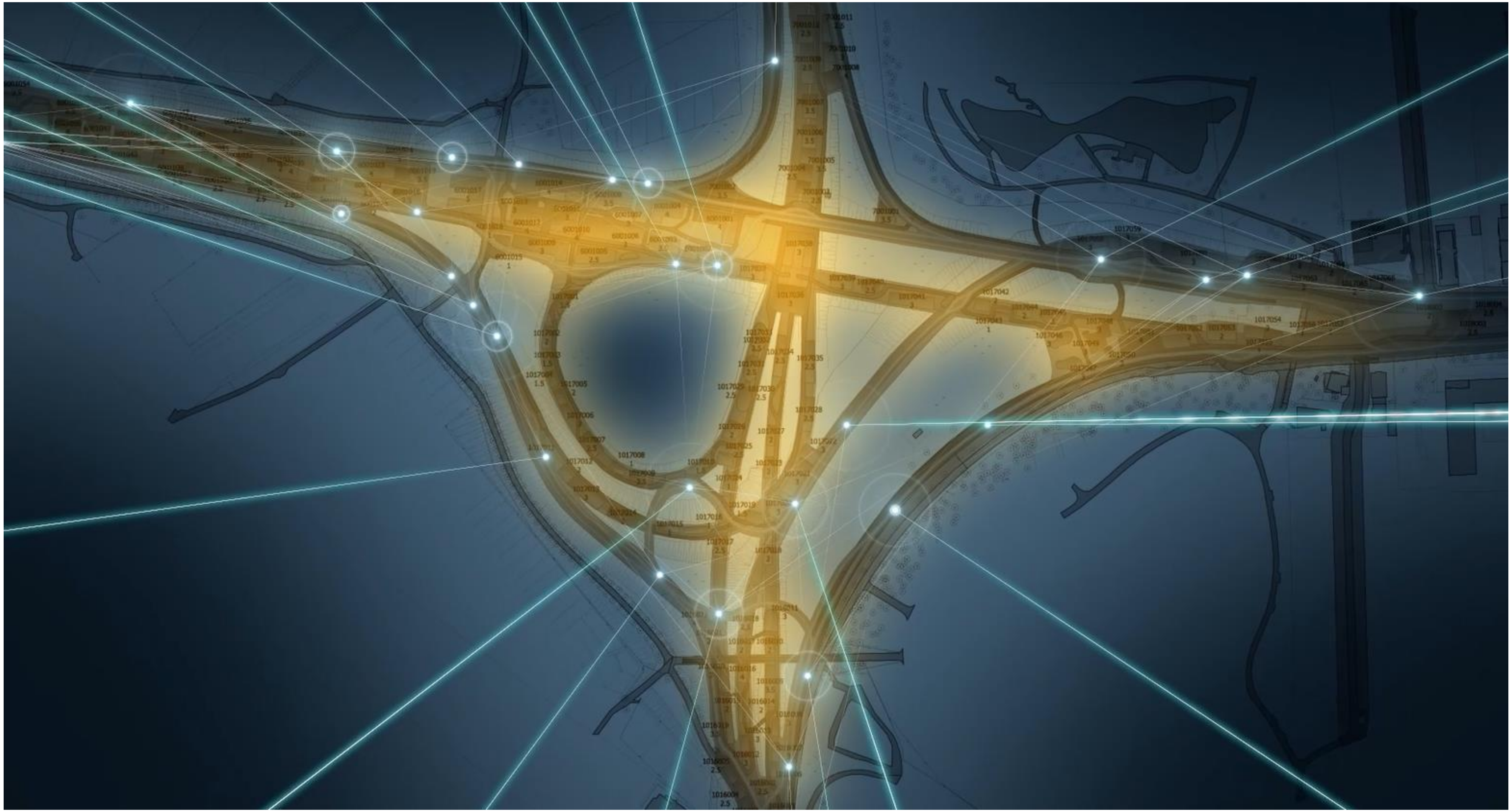
No congestion due to route optimization and on-demand system



Centrally controlled autonomous driving traffic systems are the future: In a few decades, they will be established in conurbations worldwide - with the Frankfurt bridges, Europe has the chance to become a pioneer in all the technologies needed for this purpose

Europe may have a strong automotive industry, but the prerequisites for the introduction of centrally controlled autonomous driving traffic systems are - especially legally - significantly better in other countries such as China or the USA, or the hurdles are lower and the pressure of suffering is also often higher.

This makes it all the more important to create an innovation platform in Europe where the operation and optimization of autonomous driving traffic can be tested and all the technologies and AI systems required for this can be applied. Only by means of a large live simulation can problems be eliminated, challenges overcome and learning curves run through.

Due to its size, traffic infrastructure and commuter history, Frankfurt offers the ideal location to not only create a research area for the automotive industry with the live platform Frankfurt Bridges, but also to actually significantly improve its own traffic situation: For cars and trucks on the roads, the Frankfurt bridges mean massive relief from congestion incidents, for cyclists it creates more space to introduce bike lanes, and for public transport users it results in significantly better point-to-point connections across the city for very many routes:

- You can reach countless distant destinations without changing trains
- You can often reach them much faster than by public transport
- You have comparatively short waiting times of 50 seconds to a maximum of 5 minutes
- The complete transport takes place above ground and is a safer and more pleasant alternative for children, women or elderly people than the underground or suburban train stations, especially in the evening and night hours.

The BNV is planned as a self-learning system: such a system will become better and more effective over time

The computer system that controls the vehicles learns from the incoming data: If there is always high demand at a certain stop at a certain time, this will be scheduled in advance in the future.

Major events such as soccer matches or concerts are also noted in advance. The system then calculates the demand for vehicles and deploys more vehicles at these times.

THE PLAN

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Autonomous driving and safety
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A vehicle concept in detail
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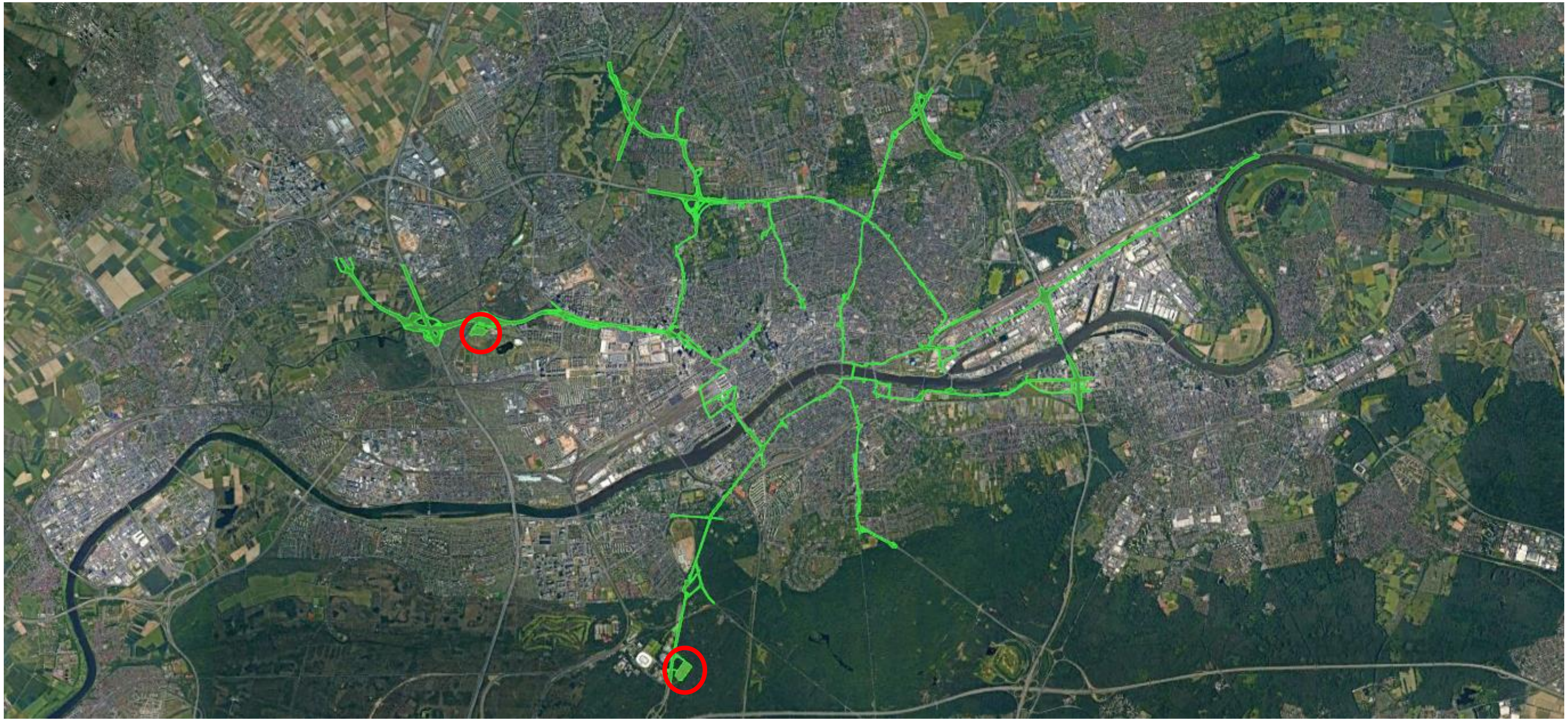
For commuter traffic into Frankfurt, there are optimal park-and-ride options at two locations: At the Deutsche Bank Park parking lot (stadium) and at the trade fair parking lot at Römerhof, convenient transfer options from the car to the local bridge transport system can be planned

There are no comparably large parking lots on the other arms of the bridge - but in isolated cases, smaller park-and-ride interchanges can be created there as well, which can relieve downtown traffic.



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Autonomous driving bridge traffic can massively relieve Frankfurt's traffic and at the same time represents a technology platform for Europe's automotive industry

The local bridge traffic system (BNV) can transport around 40 million passengers per year.

This will create many connections for Frankfurt citizens for which there was previously a public transport service, but which often work faster, without changing trains and above ground (i.e. not with subway trains) with the bridge service.

There is no comparable network of an autonomously driving system in the world, because currently everywhere too many road users still use the same lane as the autonomously driving vehicles: With the BNV, a network of protected lanes is being created on which autonomously driving traffic can be established and researched for the first time at this complexity and scale.

Old New Territory

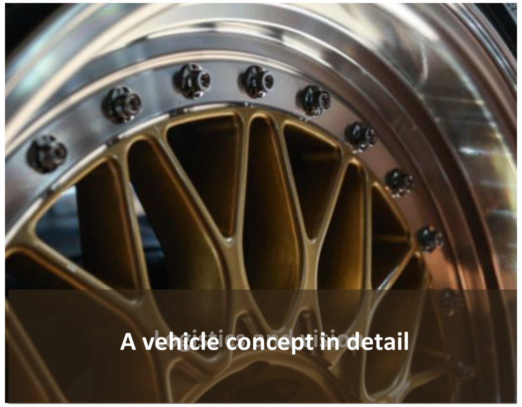
Frankfurt

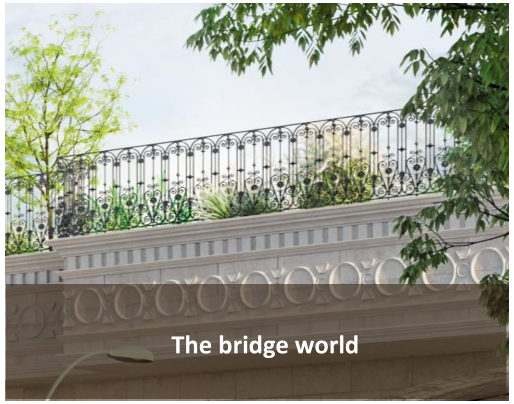

Individual transport for all


Autonomous driving and safety

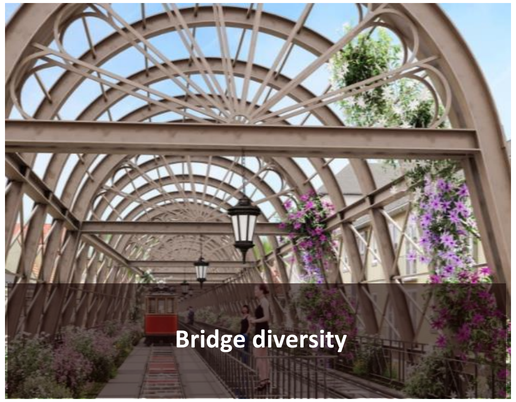

Vehicle fleet: Modern classic cars


Sustainability through technology


A vehicle concept in detail


The bridge world


Circulation system & deposit


Bridge diversity

EMPLOYEES

Architecture	Geoinformation	Urban climate - world climate	Water	Law	**Critical sparring partners:**
Image & photo	Green & Nature	Statics	Packing	Finance	Professors
Bridges	Communication	Transportation	Webpage & Design	Implementation	Professionals
Energy	Art & Culture	Technology & IT			Inspirers & Supporters