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Advanced Public Transport Operation and Modelling

The Future of Mobility

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Group 10

April 1st, 2021

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Public transport and mobility have enormously evolved over the past several decades, thanks to huge advances in technological development. The different technologies developed in Internet of Things, Big Data, mechanical and electrical domains are constantly integrated into new mobility modes to develop what could be the future of mobility. To describe our vision of what the future could look like in this domain, Rob, an employee in the Dutch Ministry of Infrastructure and Water Management in 2050, describes the transportation system in his times. In addition to the description of these modes that are now considered as emerging in 2021, the advantages and disadvantages currently seen in 2021, are considered as benefits and challenges that were overcome in 2050. This essay teleports the reader into what could be the future of mobility in the Netherlands and presents the different modes through the eyes of Rob living in the 2050 Netherlands:

The Redesigned Cities

The whole concept of the city as we knew it in 2021 was modified, putting people rather than vehicles in the center of the design. This was achieved by embracing the concept of the 15 minute city in which the housing, offices, leisure, parks, and cultural venues are reached with minimal travel time. The previous distribution of services and attractions were gradually dismantled and redistributed. The urban areas are now more accessible for their citizens and the carbon footprint of the transportation sector has been significantly reduced. This pedestrianization and proximity created by the urban reconfiguration led to an environment where social connection and natural interaction is more possible. The importance of creating closer neighborhoods was emphasized in the period of post-covid in which people discovered, back in 2020, the importance of closer connections, making our whole urban fabric more resilient to face future pandemics [2]. The three main concepts that were adopted in this redesign are the decentralization of facilities whether public or private, hierarchization of the transport system and public services by creating several layers with different coarseness, and redundancy of functions by duplicating critical components making the system more resilient [3].

The aim of this redesign was to adopt a supply-side approach to influence demand, encouraging people to use specific modes, reshaping mobility by providing the necessary infrastructure, and creating a new transport system where the personal vehicle is no longer the most appealing mode. Redistributing the urban services into more neighborhood-like areas and decreasing the access for motorized vehicles created a natural incentive to shift away from the personal cars to adopt different modes. Effectively, having limited access to several areas and the decrease in road capacity led to people shifting away from owning their vehicles to adopting active modes, shared mobility, and public transport. By re-prioritizing transport planning as seen in Figure 1, people began to change their travel behavior, as the private car became more difficult to use and active and shared modes became easier.

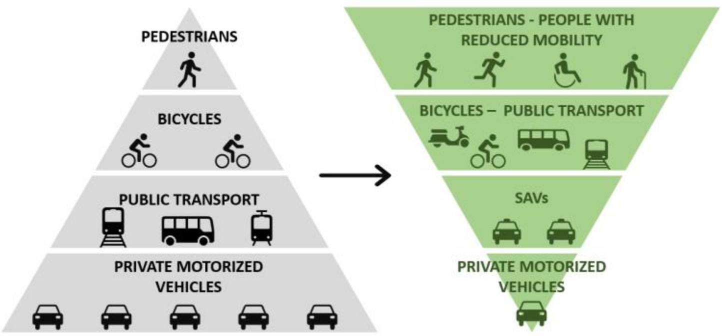

Figure 1. Urban design priorities

The following sections will discuss the different network layers of the transport system of 2050, in order from finest network to coarsest: micro-mobility, shared autonomous vehicles, urban air mobility, railway systems, and hyperloop. There will also be a discussion about how travelers access these mobility services and how land previously used for motorways has been repurposed.

Micro-mobility

As previously mentioned, the whole urban environment was redesigned to assign most of the space for the pedestrians and active mode users, limiting access for motorized modes, making the whole city safer and greener. With this type of city, micro-mobility gained a large portion of the modal split. It encompasses several modes of transportation: bike-share systems, electric bikes (e-bikes) as well as electric scooters. Unlike cars, micro-mobility carries a positive potential for human-centric cities, as much less space is required for each traveler. It can coexist with the various elements of the urban environment. It is a flexible, faster, easier and more accessible way of transportation [4]. As the cities were redesigned putting proximity in the center of the design, micro-mobility is now an essential mode of transport that satisfies the short to medium distance trips with zero emissions. For the longer distances, this mode constitutes a first-mile last-mile solution to reach the other public transport modes that link neighborhoods or cities further away; these modes are further discussed below. The micro-mobility modes are either shared vehicles operated by private companies or government, or personal vehicles. These companies were introduced in the country with certain service and regulatory requirements to organize this sector in terms of parking, environmental impact, and operations [5].

Figure 2. Flourishing of active modes [6]

Several major cities as Amsterdam, Rotterdam, Den Haag and others were redesigned according to the walkable city principle presented above, putting the pedestrians and active modes users in the center of the design. However, several other cities were not redesigned due to the high costs related to this process; hence, an improvement of the biking infrastructure, which was already relatively good, was done and the space dedicated for the cars decreased without applying fully the neighborhood concept of having everything accessible in 15 minutes. In these cities, the operation of shared micro-mobility is not financially viable for private companies; hence, the government decided to impose on these companies the condition of satisfying the demand of these areas from the profits generated in larger cities. This redistribution effect helped having shared micro-mobility vehicles even in the places where the demand makes this service financially non-viable for private companies.

The advantages of this mode are considerable since people travel using minimal space and longer distances became more accessible for all demographic groups. However, cities had also experienced negative consequences of the deployment of micro-mobility vehicles, specifically dock-less scooters and bikes. The users were leaving the vehicles carelessly in public spaces, such as sidewalks and roads. However, through the introduction of proper legislation, cities are able to oblige users to park the vehicles in specially designed spaces and make sure the companies are checking the compliance of the users. Additionally, there are now plenty of places to park, as some of the car parking was repurposed into parking for dock-less sharing systems. Another major disadvantage is the environmental impact of these vehicles. Effectively, shared bikes and scooters may have a large environmental impact depending on the lifetime and materials used [7]. However, with time, high quality material became cheaper making the vehicles more durable, and batteries evolved which decreased the environmental impact of such elements. Additionally, the installation of specific secured parking spaces distributed all over the redesigned cities where safety is deemed critical, solved the vandalism and destruction issues faced previously in 2021 [7].

SAVs

Shared autonomous vehicles (SAVs) have various roles in today's mobility, with different uses in urban, suburban and rural areas. Some hurdles had to be overcome in order to implement them, specifically the technology development and the regulations surrounding it. The first SAVs were a completely automated road-based form of transport having a small physical size and capacity, with no regular interaction of the user with the driving tasks [8]. These first SAVs were electric and were limited by speed, travel range, and size, and only ran on dedicated infrastructure that was separate from other modes. However, in order to play a role in the mobility of the Netherlands, these limitations had to be overcome. Luckily, private companies were very interested in investing in this technology, and this innovation led to the eventual creation of new generation vehicles that could travel at higher speeds (in permitted areas), operate for longer distances due to improved battery technology, and provide a range of capacities depending on the demand. Higher speeds and longer distances allowed SAVs to expand beyond their previous sole use as an access and egress mode and allowed this mode to permeate into all areas of the Netherlands.

Figure 3. SAVs integration in the urban space [9]

High-capacity SAVs currently operate as scheduled services with a predefined route during peak travel periods, operating in a similar way to what used to be known as a "bus." This makes sense for example at busy train stations, where passenger volumes are irregularly distributed based on train arrivals and travel routes from the station are predictable [10]. In off-peak travel periods and at lower volume stations, smaller SAVs operate on-demand and provide more of a door-to-door service. Now that all vehicles in the transport network are connected to each other via new generation technology for cellular networks and can easily detect obstacles and other road users, vehicle accidents have become a part of the distant past and the roads are much safer than they used to be. SAVs have also helped with package and goods deliveries, which believe it or not used to be done by large trucks, even in dense urban areas. Deliveries are loaded into delivery pods,

Figure 4. Delivery using SAV [9]

which communicate with the SAVs and load themselves onto the vehicles for routing to their destination, so it is not uncommon to share your trip with a delivery.

An important barrier to SAV adoption was the presence of an attendant, both due to government regulations and traveler perceptions. For SAVs to be cost-effective, vehicles should be monitored remotely, but prior to their implementation, studies showed that the majority of travelers would not use them because they did not feel comfortable without an attendant [8]. To help travelers adjust to this new mode, there was a transition where attendants were on-board the SAVs until travelers became confident with the technology. Once the government and the traveling public were confident in the technology, regulations requiring an attendant were relaxed and SAVs became truly autonomous.

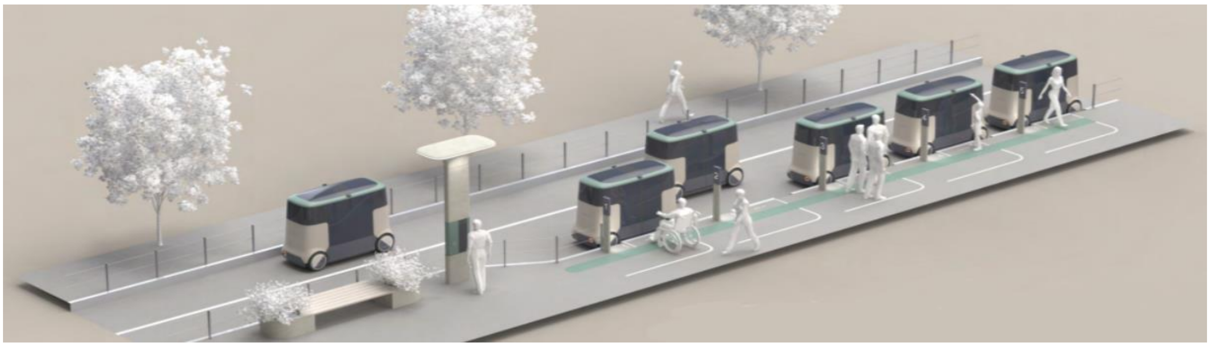

Figure 5. Rendering of busy SAVs station [9]

In urban and suburban areas, SAVs play a role mainly in access and egress to train and metro stations and for short trips within towns and cities. This is a helpful supplement to active modes, which are still often used for these types of trips in the Netherlands. SAVs have been especially beneficial for people with disabilities, as they were designed with vehicle and station/stop accessibility in mind. Children and the elderly can also be more independent than they were before, as they are not limited by a system where the primary mode is cars driven by humans. Although it took some time and there was quite a learning curve during the transition, SAVs did eventually replace the personal human-driven automobile (except for those you can go see in museums), and consequently the need for vehicle parking and multi-lane roads in urban areas. This increased the space available for other uses, such as wider sidewalks, green space and outdoor seating. The transition was especially difficult in rural areas, where for people who owned a personal vehicle, SAVs were viewed as a less convenient alternative. Therefore, some people in rural areas do own their own personal AVs. However, for people in these areas who did not have a personal vehicle or could not drive, SAVs are actually a convenient option compared to low-frequency rural bus services and help to provide access to important destinations and services. In low demand areas, a small number of SAVs wait nearby for requests, so the waiting times are never too long. You are probably wondering, how is it possible to have SAVs in low-demand areas? Well, today's SAV systems are operated in a similar way to state-run train systems, where low-productivity routes are subsidized by high-productivity routes. In this way, profitable services in more urban areas help pay for more costly services in rural areas, so that those areas still have access to this mode of transport. There have also been huge strides made in demand prediction algorithms which has really helped to reduce network waiting times, and it is also possible to book trips ahead of time. Once personal vehicle owners saw how the SAVs worked and how convenient they were, and heard their neighbors talking about how much money they saved on maintenance and insurance, they slowly began giving up their personal vehicles in favor of SAVs, with the exception of the few who prefer to have their own.

Urban Air Mobility

Another mode that was not present in the past and is gaining some momentum is urban air mobility. Effectively, many companies started with some prototypes back in 2021, like FlyNow, Airbus, and Varon Vehicles. This mode is environmentally friendly with minimal energy consumption and zero emissions, and it provides a service at a relatively low price for inner-city trips up to a limit of 15 to 50 km. This low price is achieved through the low operational and vehicle costs with the advancements in technology. The vehicles are operated in a way to minimize noise pollution in the urban environment: less than 55 dB are generated at an altitude of 150 m [11].

Figure 6. Urban air mobility vehicle [11]

The advantage of this new mode is the ability to reduce the pressure on the ground modes. This mode constitutes a faster way to travel compared to the SAVs, however, this faster service is more expensive for the user. It is used by all the user classes in our society but is more popular among people with a high value of time, like people travelling on business. In addition to business trips, this mode has an enormous potential for tourism and leisure trips [12]. It also connects rural regions that have low accessibility. Research done in 2020 expected that this mode will provide travel time savings in case the processing times are short; however, it was expected that this mode cannot substitute the ground modes and relies on the latter for access and egress modes [13].

The urban air mobility network is constituted of "vertiports" and permanent virtual lanes. The virtual lanes connect the different "vertiports" making this mode of transport safe and organized [14]. A problem was mentioned previously about the need of infrastructure and land availability to operate this mode [13]. It was estimated back in 2020, that a small vertiport for 10 vehicles requires 4160 m^2 to process 5400 passengers per day; a larger one for 50 vehicles requires 20,000 m^2 to process 130,000 passengers per day [12]. Solutions were found to solve these issues, currently many vertiports are located on top of existing buildings so they do not hinder the urban fabric. All the vehicles are connected to one traffic management unit managed using AI, this air traffic management coordinates with the vehicles and plans their paths accordingly to avoid any conflicts.

Although this mode does not emit a lot of noise, one major disadvantage and opposition is the visual pollution created by these flying vehicles. Some solutions were suggested to limit the virtual lanes created to places that do not hinder the well-being of citizens. Such as having the virtual lanes following train tracks or other major transport infrastructure hence, minimizing the perceived noise, risks, and visual impacts [12].

Railways

Rail travel within the Netherlands has not changed too much in the past 30 years, but some changes were implemented to accommodate the increase in travel demand. Travelers who previously used a personal vehicle had to switch to a new mode for long-distance travel within the country, which in this case is heavy rail. Here we distinguish between the main line network, regional network, and local networks within large cities.

Figure 7. Rendering of a train station [15]

The main line network has been updated with additional routes and new technology to allow for increased capacity. The rail network has evolved to include additional routes that reduce travel time between popular origin-destination pairs and remove gaps in the network. This helped to make the network more robust by increasing its meshedness, which is important because nowadays, any disruption impacts significantly more travelers than it would have back in 2021. The main technologies that have allowed rail to increase its capacity are the European Railway Traffic Management System (ERTMS) level 3 and level 4 Automatic Train Operation (ATO). In addition to allowing interoperability throughout all of Europe, ERTMS level 3 has improved safety, increased speeds and capacity, and has lower maintenance costs. The main features of this system that allow such a capacity increase are that it no longer relies on trackside train detection equipment or legacy signaling systems. Instead, mobile communications are used for train detection, which allows for the use of a moving block system where trains can be spaced closer together as they are no longer limited by the block length [16]. This level of ERTMS did take some time to implement due to concerns about backup in the case of train detection system failure. To solve this problem, conventional trackside train detection is used as a back-up, which is known as ERTMS level 3 hybrid, although the technology is continuing to evolve, so this may not even be necessary in the future [16]. The introduction of level 4 ATO, unattended train operation, has also contributed to increased capacity, improved punctuality, increased energy efficiency, more flexibility, and increased cost-effectiveness [17]. At the time, ATO level 4 had already been implemented in metro systems around the world, but many challenges had to be overcome to implement this technology on mainline railways. These challenges included dealing with the presence of mixed passenger and freight traffic, complex station track layouts, and large networks [17]. However, due to the involvement of private companies in the accelerated development of ATO and the financial support of the government to improve the infrastructure, ATO was eventually able to be implemented on mainline railways. Even with changes to the network and improved technology, traveler demand was expected to outpace the supply of rail services. Therefore, it was decided to begin operating larger trains, which is how we got the triple deck trains that we know today. It may also be necessary in the future to lengthen trains, and by consequence the station platforms, which will allow us to accommodate even more demand.

On the regional network, where routes often do not have sufficient demand to operate with a frequency of 15 minutes or less throughout the day, demand-responsive rail has been implemented to reduce travel times. This technology is used as a replacement for scheduled heavy rail services on these parts of the network, where vehicles move autonomously through the network based on passenger requests [18]. Vehicles are much smaller than the trains used for heavy rail service, with a maximum of 100 seats, although most are much smaller. The goal of the system is to provide as many passengers as possible with a transfer-free trip, so each vehicle often has its own route [18]. One concern with the introduction of this new mode was that simulations showed that there was an overall average travel time savings on the network, a small percentage of passenger demand was left unserved. To serve these passengers, a significant increase in fleet size would be required, so a cost-effective solution was needed to ensure the fulfillment of all requests [18]. This problem was especially a concern in rural areas which may have low-yielding OD pairs. However, it was discovered that by adjusting the network configuration in a way that makes these areas easier to serve, and due to the modal shift leading to increased demand in these areas, all requests could be fulfilled [18]. Other challenges for the implementation of these services included high investment costs and the initial lack of interest in this technology in the market. However, the interest of private companies in this new way of travelling increased after seeing the success of other automated modes, which helped fund research and development to come up with ways to reduce the investment costs [18].

In the past, trams and metros were the primary rail-bound modes of public transport within large cities. Trams are no longer in operation, as they were replaced by SAVs (which have superior flexibility) and their tracks were removed, since they pose a safety hazard for cyclists. Metros are still a popular mode for transport within cities, and systems have been expanded where they existed previously, and some new metro networks have even been built in growing cities that did not need them before. Metros can operate at high speeds, due to implementation of Communication Based Train Control (CBTC) and level 4 ATO, dedicated and separate infrastructure, and the fact that their routes are not restricted by the street network. CBTC allows trains to use a moving block system where trains communicate their positions via radio, which has allowed for the necessary capacity increases to accommodate demand, in addition to the previously discussed benefits related to ATO [19].

Railways have not significantly changed their form but have found ways to improve their services, with much higher capacity and finer networks in urban and most suburban areas, and demand-responsive rail in some suburban and most rural areas. For travel outside of the Netherlands, other forms of travel are used to provide a sustainable alternative to air travel.

Hyperloop

The development of technology and the willingness of people to travel longer distances in shorter time emphasized the importance of introducing innovative modes such as the hyperloop. Effectively, the hyperloop is an energy-efficient mode of transport where a pressurized pod travels in a (near) vacuum tube through magnetic levitation. The pods travel at speeds higher than 1000 km/h linking several trips in a minimal time compared to traditional modes. This mode lies between air travel and train travel, where it merges the flexibility and comfort of train travel with the speed and reliability of air travel [20].

Figure 8. Hyperloop tubes [20]

It was determined to locate the hyperloop hubs between highly used origin-destination cities to provide a competitive mode of international travel. The different modes mentioned previously constitute a more detailed network compared to the coarser hyperloop network. Effectively, the Netherlands houses few stations located in the main cities like Amsterdam and Den Haag. Passengers use this mode to travel to other cities all around Europe in minimal time. What was unimaginable 30 years ago is now a reality: you can meet a friend in Paris in the morning and come back to Amsterdam for lunch. Passengers are able to use the other modes presented to access the hyperloop hubs. The hyperloop concept lies in coordination with the on-demand culture where the pods are filled with 28 to 50 passengers, and head towards the desired city with no stops or any transfers. The pods have effectively limited capacity compared to traditional trains; however, the main advantage is the high frequency that could be achieved. Effectively, the high communication connectivity of the system and automated operation allows keeping very low headways between pods and achieve frequencies of 2 pods per minute [20].

In addition to passenger transportation, the hyperloop allows energy-efficient, fast freight transport over long distances, optimizing the supply chain and contributing to the physical internet. Effectively, goods can be transported in an efficient and fast way between cities and hubs. The Netherlands is equipped with one main hyperloop freight corridor linking the different industrial zones and ports as seen in Figure 9.

Figure 9. Freight hyperloop corridor in the Netherlands [21]

Some of the past critiques related to the hyperloop were the ability of this mode to provide safe and reliable services. Effectively, traveling pods in near vacuum could magnify any hazard and accident: the lack of maintenance, or breach in the system could lead to fatal consequences. However, safety protocols were developed by several companies and parties for several years to mitigate and prevent any hazard that could occur in the goal of providing a mode that has a similar or even better accident occurrence rate compared to the train or plane. To minimize the risk of terrorist attacks in the pods leading to fatal outcomes, the hyperloop stations are designed to provide a seamless experience while performing the necessary safety checks. The main drawback of this mode were the extensive investments needed. Effectively, back in 2020, AECOM estimated the capital investment costs needed to be around $56.4M per km for a 500 km route [22]. However, given the large environmental benefits that could be gained from this new mode by effectively replacing polluting domestic air travel, it was decided that the hyperloop was worth the price tag. Additionally, some initial coordination complications arose between the government and private companies, but proper legislation was issued to clarify the uncertainty and make this project a reality.

Mobility as a Service

Another main component of our modern transport system is the inclusion of all the services available, whether shared micro-mobility vehicles or on-demand SAV trips, into one mobile application platform, known as *EuroWay* (which helps you travel "your own way"). *EuroWay* emphasizes the MaaS paradigm and simplifies the processes to request, make, and pay for a trip for a certain mode. To keep the competitiveness between different modes but still maintain system unity, each mobility company or government that is approved for passenger service is required to integrate their services into this app. As is evident from the name, *EuroWay* is not only limited to the Netherlands but is used all over Europe, simplifying the process for both locals and visitors, and enabling fluent mobility all over the EU. Services in the app are offered based on traveler location. *Euroway* has been especially beneficial for long-distance travel in the EU on international trains, which have become so popular due to the rail service improvements made possible by ERTMS implementation and hyperloop, that polluting domestic airline travel within the EU has become a thing of the past.

Figure 10. All modes in one app [23]

Of course, one of the most critical aspects of developing this new transport system was understanding how to make it accessible for all travelers. The majority of Dutch people are quite experienced with digital devices such as smartphones and smartwatches where *EuroWay* is available. However, this was not the case for everyone, especially at the start of the transition process, and it is important for all travelers to be able to use this system regardless of digital literacy or internet access. For travelers who are not comfortable using *EuroWay*, SMS or phone calls through the *EuroWay* call center can be used to request trips and payment can be made with a smartcard once on-board the vehicle [24]. Additionally, at train stations, digital kiosks help you to plan and reserve your trip, and payment for the trip can be made with a bank card, which is especially helpful in the unfortunate situation when you do not have your smartphone with you. The kiosks are especially helpful for the visually impaired, as they can also accommodate verbal requests made by passengers and respond in a helpful way, thanks to the improvements in artificial intelligence. Mobile robot assistants were pioneered at some larger stations to help travelers find kiosks, provide directions and even escort people to different parts of the station when requested. These robots are especially used by infrequent travelers and have also helped people with disabilities to identify accessible paths and entrances/exits and provide any additional assistance that is needed. Given their success at large stations, the mobile robot program has been expanded and gradually, robots have been added at stations and transport hubs throughout the country.

Decommissioning Motorways

Despite all the effort that went into expanding urban motorways over the past 100 years, they were torn down after the significant reduction in the use of personal vehicles. The space taken up by multiple lanes per direction, the on- and off-ramps and interchanges was large and wasteful, and most of this land was repurposed to build new housing, although some was used to expand the rail infrastructure network and restore green space. There was a housing shortage in the Netherlands until recently, but this nationwide construction of housing really helped fill gaps in the urban housing supply and helped the housing market better keep up with demand from population growth. This also helped to improve the connectivity of street networks in these areas, as the removal of these motorways meant that parts of cities were no longer physically separated from each other. Motorways between cities still exist for SAV use and freight, although they are no longer called motorways, they are called *shareways*. By taking this space that was previously allocated to personal cars and giving it back to people, the health and quality of life for the Dutch has improved drastically.

The Bigger Picture

This multi-level transport network has significantly improved mobility within the Netherlands, compared to what it was 30 years ago. The highest levels of the network consist of rail-bound modes: hyperloop, mainline heavy rail, regional rail, and local rail. Hyperloop provides functions for both passenger and freight transport, with passenger transport between Amsterdam, Den Haag, and other EU hyperloop stations, allowing for fast and sustainable international transport of people and goods. Heavy rail is used for long distance travel within the Netherlands, and is similar to the 2021 Dutch rail system, but with increased capacity due to network and technology upgrades. Regional rail is operated on-demand to provide a fast travel option for people living outside of major urban areas, and updated metro systems are used by travelers within dense urban areas. One network level below rail travel are SAVs and urban air mobility, which operate in all parts of the country, although with slightly different functions in urban, suburban, and rural areas. SAVs mostly serve as an access and egress function while air travel is usually used as the primary mode for trips, although there are exceptions to both. The lowest network layer belongs to active modes, which are heavily used for short trips in all parts of the country, although some active modes such as e-bikes and e-scooters are used for longer trips. Active modes are both shared and privately owned, which makes them accessible all over the country. Changes to the transport network were also supported by some changes to urban design, which follows the 15-minute city principle. After the 2020-2021 COVID-19 crisis, it became clear that the transport system needs to be more flexible in order to deal with future pandemics. By relying more on active modes and small SAVs, the Netherlands is better prepared to keep the economy functioning during the next (hopefully not) pandemic. All modes are integrated into a central mobility platform, which can be accessed in several ways depending on the level of comfort travelers have with technology. Due to the development of these modes, the personal vehicle, which used to be the dominant mode in the Netherlands, has been almost entirely phased out and the land has been repurposed, as in the case of urban motorways. Although the transition was not easy or cheap, the benefits have been enormous: increased sustainability, safer, healthier, more accessible and equitable cities, where the travelers are the center of the transportation system.

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