Agora Verkehrswende

On Autopilot to a More Efficient Future?

How Data Processing by Connected and Autonomous Vehicles Will Impact Energy Consumption

ANALYSIS

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Imprint

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Preface

Dear readers,

"Even the internet has a tailpipe" – this was the pithy title of an article in a major German newspaper a few years back.[1] The article explored our growing reliance on data centers, including in particular the power consumption entailed by our daily use of smartphones and computers. Of course, your electronic device does not release carbon dioxide directly. However, it does cause emissions elsewhere. Remote servers must handle every search, post, and download, leading to increased power consumption behind the scenes. While power generation from renewables continues to increase in Germany, a significant share is still attributable to the burning of fossil fuels.

The car is well on its way to becoming a particularly hefty "mobile device." Computer-based systems already assist with navigation and parking, and the act of driving is also becoming increasingly automated. The large-scale adoption of autonomous vehicles will require the processing of enormous volumes of data. Autonomous vehicles are expected not only to gather data about their surroundings through onboard sensors, but also to retrieve and share data remotely through dedicated backend systems. In this way, the autonomous vehicles of the future won't just run on electricity, but also on bits and bytes.

There is a pressing need to consider the additional power demand that will be associated with connected and autonomous vehicles, even given the full decarbonization of the economy. For clearly, renewable electricity is a precious commodity that will be in higher demand in ever broader areas of the economy as we move closer to net zero emissions.

Discussions regarding the impacts to power demand that will result from the broad adoption of connected and autonomous vehicles are only just beginning. A frequently voiced opinion is that autonomous vehicles will reduce energy consumption, thanks to more efficient traffic routing and driving performance. However, little attention has been devoted to examining the additional power consumption that will invariably result for supplementary onboard systems and for networking the vehicle to other vehicles (V2V), to road infrastructure (V2I), and to backend servers (V2C). In a previous study titled "Vehicle Automation and its Consequences," published in August 2020, we took a broad look at opportunities and risks in the area of sustainable mobility. Our research indicates that the transport sector will not automatically become more sustainable through the adoption of autonomous vehicles. Rather, autonomous vehicles need to be intentionally developed and deployed in a manner that serves the goal of decarbonization. And this can only occur on the basis of informed debate that culminates in targeted policy measures.

This study aims to stimulate further research and debate regarding the energy-relevant aspects of connected and autonomous vehicles. In particular, we hope to spotlight opportunities and clarify latent challenges, with the ultimate goal of supporting evidence-based policy discussion. To be sure, autonomous vehicles can make an important contribution to the Verkehrswende ("transport transformation") – yet they won't do it automatically.

On behalf of the Agora Verkehrswende team,

Christian Hochfeld
Berlin, 11 January 2021

1 Maak, Niklas: Auch das Internet hat einen Auspuff, in: Frankfurter Allgemeine Zeitung (Jan. 13, 2018), p. 9.

Recommendations for Action

Depending on how connected and autonomous vehicles are adopted, strongly divergent impacts to net energy consumption in the transport sector will result. Autonomous vehicles may reduce energy consumption if they are adopted and driven in an efficient manner. However, significant increases in energy consumption are also possible. The factors impacting the efficient deployment of automated vehicles and associated technologies should be discussed by stakeholders now, at the early stages of development. Based on the findings presented in this study, Agora Verkehrswende recommends action in the following areas:

1 Encourage the efficiency of automation components in order to limit additional onboard power consumption.
The energy efficiency of the components required for connected and autonomous driving is particularly important for electric vehicles, as they directly impact vehicle range. European vehicle emissions standards should be reformed to focus on energy efficiency, rather than carbon emissions, while explicitly taking automation components into account. We assume that the additional onboard energy consumption of fully autonomous vehicles can be limited to 270 watt-hours per 100 kilometers driven by 2050, given steady efficiency improvements.

2 Design vehicle networking systems using a "lean" approach ("no more than needed").
Investment costs and associated energy consumption will rise in direct relation to the scope of data communication that takes place between vehicles, infrastructure, and backend systems. As a general principle, vehicles should be designed to operate safely without the need to communicate remotely with other vehicles or infrastructure. In the design of the overall system for connected and automated vehicles, the advantages of additional connectivity should be weighed against increases in energy demand. Furthermore, vehicle connectivity should rely on WiFi rather than cellular networks whenever possible, for efficiency reasons.

3 Steamline the scope of data transfer to and from the vehicle.
Each connected and autonomous vehicle is expected to generate an enormous amount of data: between 1.4 and 19 TB per hour. The amount of data transmitted to and from other vehicles, traffic infrastructure, and backend servers will be a crucial determinant of the efficiency of the overall system, and should thus be kept to a minimum. Indeed, data transfer to and from the vehicle of just 0.8 TB per hour would already offset the potential efficiency gains of autonomous vehicles in other areas. Streamlining in this area (e.g. using big data analysis techniques) will be essential for ensuring that the benefits of connected vehicles for traffic routing and road safety do not lead to inordinate increases in energy demand.

4 Include connected and autonomous vehicles in vehicle sharing services and public transport networks, in order to counteract increased private-vehicle mileage.
The augmented convenience and functionality of self-driving cars is likely to encourage increased reliance on private vehicles. However, the potential energy savings of autonomous vehicles would be wiped out completely if fleet mileage were to increase by just 1 to 2.6% up to 2050. Accordingly, stakeholders should work to make vehicle operation as efficient as possible while also encouraging integration with sharing services and public transport.

5

Pass targeted regulations to promote the efficiency of the IT infrastructure used to manage vehicle networking.

The impact that networked and automated vehicles will have on energy consumption will depend in part on the efficiency of associated IT infrastructure and systems. According to our estimates, in the initial years of connected and autonomous vehicle adoption, the supplementary energy consumption induced by networking infrastructure will sharply offset – and may even overshadow – the efficiency gains associated with more efficient driving performance and routing. Furthermore, over the long term, the net energy savings achieved with connected and autonomous vehicles will, at best, be equivalent to 10% of the energy required for the propulsion of mid-sized electric car today – that is, assuming a scenario with minimal networking. More extensive networking will reduce this figure to 4%, even given efficiency improvements. For this reason, regulators should devote special attention to promoting the efficiency of vehicle networking infrastructure. Furthermore, the effects of such regulations on energy consumption should be monitored on an ongoing basis so that regulators can make corrective adjustments as needed.

Content

1 | Introduction

The transport sector is in a state of flux. New digital technologies are changing how we get around, by allowing us to compare and combine various transport and routing options. Our mobility behaviour is also being transformed by new sharing services. However, the transport sector is only at the very outset of a comprehensive digital revolution. According to experts, coming advances in vehicle automation and networking will set into motion far-reaching change in the transport sector and in mobility behaviour.

Autonomous vehicles have been in development for many years. The Society of Automotive Engineers (SAE) has defined five different levels of automated driving, to refer to the ascending levels of functionality assumed by the vehicle itself. At level 5, the final stage, the vehicle is fully autonomous and the driver is merely another passenger.

While autonomous trains have been a reality for many years, and high automation (level 4) is also available for planes, on the road, we remain at the level of conditional automation (level 3). Due to the complexity of the road environment, including the diversity of possible road users, we still face critical hurdles to fully reliable autonomous vehicles. There is no consensus between manufacturers and researchers on when the market introduction the final two SAE levels (high and full automation) will occur. While European Road Transport Advisory Council anticipates full automation to be market ready between 2020 and 2026 (ERTRAC 2019), the German Association of the Automotive Industry (VDA) predicts market readiness between 2025 and 2030.

A range of companies are also developing solutions for networking vehicles with each other (V2V), with the cloud (V2C) and with road infrastructure (V2I). Most concepts for the future of autonomous vehicles presume the integration of such networking solutions, as data exchange between vehicles is expected to be an important enabler of greater transport system efficiency and convenience. Accordingly, almost all manufacturers are working on the integration of vehicle networking technologies that will create additional value for the vehicle owner. However, autonomous vehicles are also being designed to operate on a fully independent basis, such that networking is not required for safe and convenient operation.

To be sure, autonomous vehicles have engendered high hopes for the future of transport beyond greater convenience. In a 2015 strategy paper, for example, the German transport ministry sees automated and connected vehicles as a crucial catalyst for greater transport system efficiency, improved road safety, and lower transportsector emissions (BMVI 2015). What is more, driverless transport systems are expected to enable new, demand-driven mobility services that rely on the flexible and efficient combination of various transport options. This could reduce reliance on privately owned passenger vehicles, thus accelerating the transition to a transport system that is energy efficient and carbon neutral. At the same time, however, there is also the danger that the unregulated introduction of autonomous and connected vehicles would make private vehicle ownership even more attractive, thus decreasing reliance on public transport. Against this backdrop, an issue that has garnered surprisingly little attention thus far is whether and to what extent automated and connected vehicles would lead to increasing energy consumption.

This paper seeks to quantify the impacts to energy consumption that would result from connected and autonomous vehicles (CAVs) in road transport while considering energy consumption by vehicles as well as by associated IT and communications infrastructure. In this connection, a focus is placed on the energy consumption generated by automated vehicle use. No effort is made to quantify the energy consumption associated with system manufacture or disposal.

Despite uncertainties concerning when automated vehicles will be market ready, many experts consider this impact analysis urgently necessary in order to identify possible negative effects on energy consumption and greenhouse gas emissions at an early stage. Accordingly, this paper intends to expand the evidence base on the environmental effects of automated vehicles, in part to shed light on the potential need for automation efficiency standards. To this end, this paper illustrates the implications of connected and autonomous vehicles (CAVs) at the level of an individual vehicle with a time horizon up to 2050.

Examining the effects of a well-established system that consists solely of fully automated and networked cars is not the aim of this paper. Rather, it seeks to consider the penetration rate in the German vehicle fleet that can be expected by 2050 under real market conditions. A secondary goal of this study is to highlight potential action measures that would help to facilitate climate-friendly transport on the basis of vehicle automation and networking.

1.1 Definitions

The development of vehicle automation typically progresses in an evolutionary fashion over five stages. The German government and industry actors rely on the reference system developed by SAE International (2018), which defines five levels of driving automation.

- Level 1 – Driver Assistance
  The system provides for automated speed control or steering, but the driver must be ready to retake full control at any time.
- Level 2 – Partial Automation
  The system provides for automated speed control and steering for a certain period of time or in specific situations. The driver must permanently monitor the system and be ready to retake full control at any time.
- Level 3 – Conditional Automation
  The vehicle is capable of performing all driving functions under certain limitations. The driver no longer has to monitor the system constantly, but must be able to take over completely within a reasonable period of time.
- Level 4 – High Automation
  The vehicle is capable of performing all driving functions under certain conditions.
- Level 5 – Full Automation
  The vehicle is capable of performing all driving functions under all conditions. The driver may have the option to control the vehicle.

When vehicles are networked with each other (V2V), to the cloud (V2C) or to transport infrastructure (V2I), there are two basic possibilities for data transmission: WiFi or cellular signal. The WiFi standard is defined by Institute of Electrical and Electronics Engineers (IEEE) under the designation 802.11. Numerous advancements in WiFi have been developed in recent years (especially in terms of bandwidth and frequency). 802.11p is a WiFi sub-standard that was developed for networking vehicles and road infrastructure. Known as ITS-G5 in Europe, 802.11p is called Dedicated Short Range Communication (DSRC) or Wireless Access in Vehicular Environments (WAVE) in the United States. It enables communication between network objects at vehicle speeds of up to 200 km/h and at ranges of up to 1000 metres. WiFi connectivity can be used for V2V, V2C and V2I networking. In addition to WiFi, the cellular network can also be used for V2V and V2C networking. In this connection, use of the 5G network standard is preferable, as data transfer rates are significantly faster than LTE Advanced (10 versus 1 Gbit/s; cf. Herrmann and Brenner 2018). 5G networks also permit decentralised IT processes at base stations. This reduces latency to 10–100 milliseconds, which can increase safety, especially given high vehicle speeds.

Since WiFi technology does not depend on cellular network coverage, it is particularly suitable for automated vehicles, not only to increase safety (e. g. with collision warnings), but also locally to improve traffic flow (e. g. with intersection management). Cellular networks, by contrast, are particularly well suited for broad-based services, such as traffic management systems, gridlock prediction and cooperative driving. They also enable digital maps to be updated with important information required for automated vehicles to operate safely. Such updates can also be transferred to the vehicle via WiFi at the start of a journey, however.

1.2 Research method

In order to estimate the energy consumption effects of vehicle automation, this study relies primarily on a review of secondary literature on energy consumption and on the technical design of systems for vehicle automation and networking. Based on our research, we elaborate two potential scenarios for the development of vehicle automation and networking. One aim of this exercise is to illustrate the uncertainties that still exist today regarding future technical developments, including the attendant implications for the energy consumption of CAVs in comparison to standard vehicles. In order to validate and refine the assumptions underlying the two scenarios, we also interviewed six national and international experts from the domains of academia and industry. The findings emerging from these interviews have been incorporated into our scenarios and calculations.

In the next step, we estimate how connected and autonomous driving will impact the efficiency of a vehicle's final energy consumption, not only due to additional electrical consumers (e. g. sensors) but also due to additional weight. In order to take into account attendant energy demand effects at the macro level, we also estimate implications for energy consumption attributable to cellular-based networking, required backend servers, and other IT infrastructure. Lastly, based on the results of these calculations and the expert interviews, we distil recommendations for action for policymakers and industry executives, while pointing to knowledge gaps where further research would be advised.

2 | Automation and networking scenarios

When performing technology impact assessments, a key challenge is to manage uncertainty regarding future technological developments. While vehicle automation has only just crossed the threshold to conditional automation (level 3), numerous uncertainties persist concerning when levels 4 and level 5 will achieve market readiness. Even greater unknowns exist regarding the scope and speed with which networking technologies will be introduced, whether between vehicles (V2V), to the cloud (V2C) or to road infrastructure (V2I). While newly registered vehicles are all outfitted with some level of networking functionality (emergency-call systems have been mandatory in the EU since 2018), networking functionality is anticipated to expand to a much broader range of applications in the future, such as cooperative driving (Hermann and Brenner 2018). In order to spotlight these uncertainties and illustrate the potential scope of future developments, we have elaborated and refined two scenarios as part of this technology impact assessment.

While automotive manufacturers and suppliers have been pursuing a range of different approaches, they all agree that ensuring the safety of vehicle occupants and third parties is a paramount concern. As a result, one fundamental engineering requirement across all levels of automation is that safe operation of the vehicle must be possible without the need for additional remote connectivity. Several prerequisites would have to be fulfilled for this limitation to be overcome: networking functionality in all vehicles; a seamless and failproof backend accessible by cell or WiFi connection; and fully networked road infrastructure (road signs, traffic lights). While manufacturers and suppliers will recoup their automated-vehicle development costs through market sales, a key unresolved question is who will cover investment costs for the connected infrastructure. Manufacturers are not yet collaborating on this issue, nor is it certain whether and to what extent the public sector will bear such costs. The experts we consulted also expressed very different opinions on this matter. The payment of patent royalties for cellular-based V2X applications is another unresolved issue hindering broader vehicle networking.

At the same time, the synergistic benefits that would result from combining vehicle automation with networking are undisputed. Data exchange between vehicles regarding special conditions – such as road hazards – can additionally improve the safety of the overall system. In addition, V2X networking will open up new frontiers in cooperative driving. A more effective use of existing road infrastructure promises to increase capacity by up to 40 % (Krause et al. 2017). However, this would require a very high share of level 4 or 5 connected and autonomous vehicles in the vehicle fleet.

In the area of future market trends, the studies diverge considerably, not only with a view to market readiness, but also concerning the speed of diffusion in the vehicle fleet. While some studies presume 100 % diffusion of level 4 – or even level 5 – by 2050, other studies conclude the vehicle fleet will only contain a small percentage of level 4 or 5 vehicles by 2050. The latter studies take into account user acceptance and consumer willingness to pay significant surcharges for CAV equipment. Trommer et al. (2016), for example, assume a 17 % penetration rate for level 4 and 5 passenger cars in Germany by 2035. Altenburg et al. (2018) estimate a level 4 and 5 fleet share of up to 35 % in 2050. Krail et al. (2019), by contrast, calculate that in 2050, 36 % of the German vehicle fleet will consist of level 4 and 5 vehicles. In this study, the authors take into account user acceptance, willingness to pay, and automation-technology cost declines. Both of our scenarios are based on the market growth trends developed in the comprehensive study by Krail et al. (2019). Krail et al. assume that level 3 will be available starting in 2020, level 4 in 2025 and level 5 in 2035 (at the earliest). It is also assumed that advanced automation technology will initially be available in luxury vehicles, and will later diffuse to mid-size and compact cars 5 and 10 years later, respectively.

While our scenarios are identical with a view to the market diffusion of automated vehicles, they differ in terms of the adoption and characteristics of networking technology. In our Minimal Networking scenario, it is assumed that apart from ad-hoc networking between vehicles (V2V) using the 802.11p standard or cell networks, there is no further networking with a backend or road infrastructure. Data exchange in this scenario is essentially confined to the immediate vicinity of the vehicles (300–1000 metres). Specifically, cell-based V2C networking only takes place for updating maps. Furthermore, this scenario assumes that road infrastructure (V2I) will not be significantly networked up to 2050.
In this way, one hallmark of the Minimal Networking scenario is scepticism as to whether the investment costs

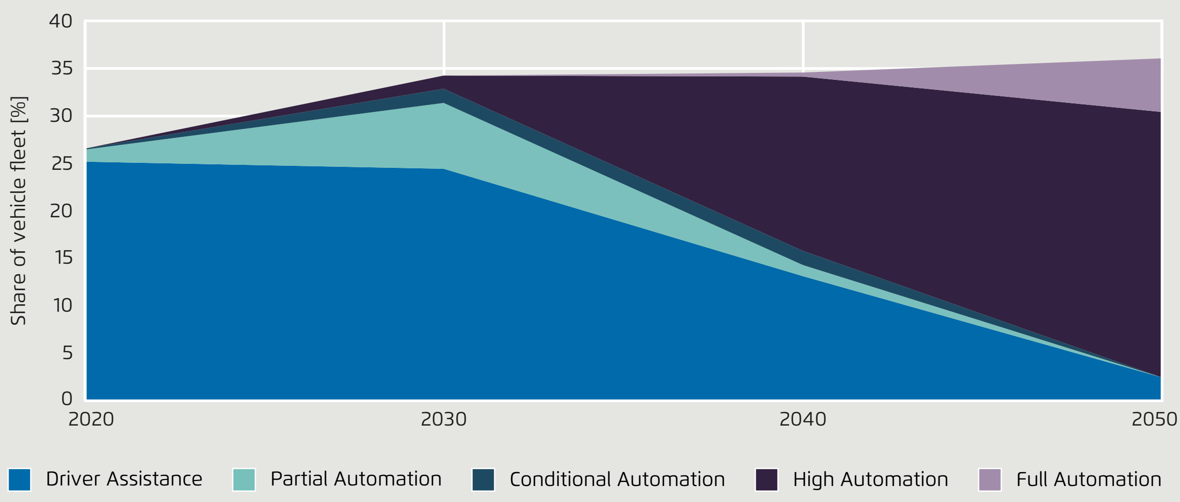
for networked road infrastructure can be covered by 2050, a view that was expressed by several experts.

As a counterpole to the Minimal Networking scenario we have also developed an Efficient Networking scenario. This scenario assumes that networking between vehicles (V2V), to the cloud (V2C) and to road infrastructure (V2I) can be predominantly realised by 2050. Under this scenario, data transfer to and from the vehicle takes place on decentralised servers using 5G cellular connectivity or the IEEE 802.11p standard. The decentralised servers, which are based on the network architecture of MEC (Multi-Access Edge Technology), enable rapid transfer of notifications, mapping updates and additional information from manufacturer-specific databases to and from the connected vehicles. The decisive advantage of the MEC concept is distributed processing, which enables short latency times that cannot be realised with a centralised backend or cloud solution. Especially at higher vehicle speeds, this advantage can be decisive for road safety. MEC technology has already been successfully tested in various research projects, including MEC-View (2020) and Car2MEC (2019). In our scenario it is assumed that the MEC servers can be installed on all German autobahns by 2050, with one server covering a maximum of 20 kilometres of road. Our scenario additionally assumes 50 % MEC coverage on highways (viz. *Bundestrassen*), 20 % coverage on rural roads (*Landstrassen*) and 10 % coverage on district roads (*Kreisstrassen*). Furthermore, we assume linear market growth up to 2050.

With a view to networking, the Efficient Networking scenario assumes that by 2050, all relevant traffic signs and lights will be networked, including in particular speed limit signs and signalling systems important for safe and efficient operation. In addition to options for networking lights and signs, researchers are also testing the installation of sensors along roads. From a present-day perspective, however, equipping roadways with networked sensors by 2050 seems unlikely, even under an Efficient Networking scenario, in view of the immense investment costs this would entail. Accordingly, we do not presume the installation of roadway sensors in this scenario.

Another aspect not taken into account in either scenario is the additional energy consumption that would be associated with the increased use of multimedia by drivers and passengers.

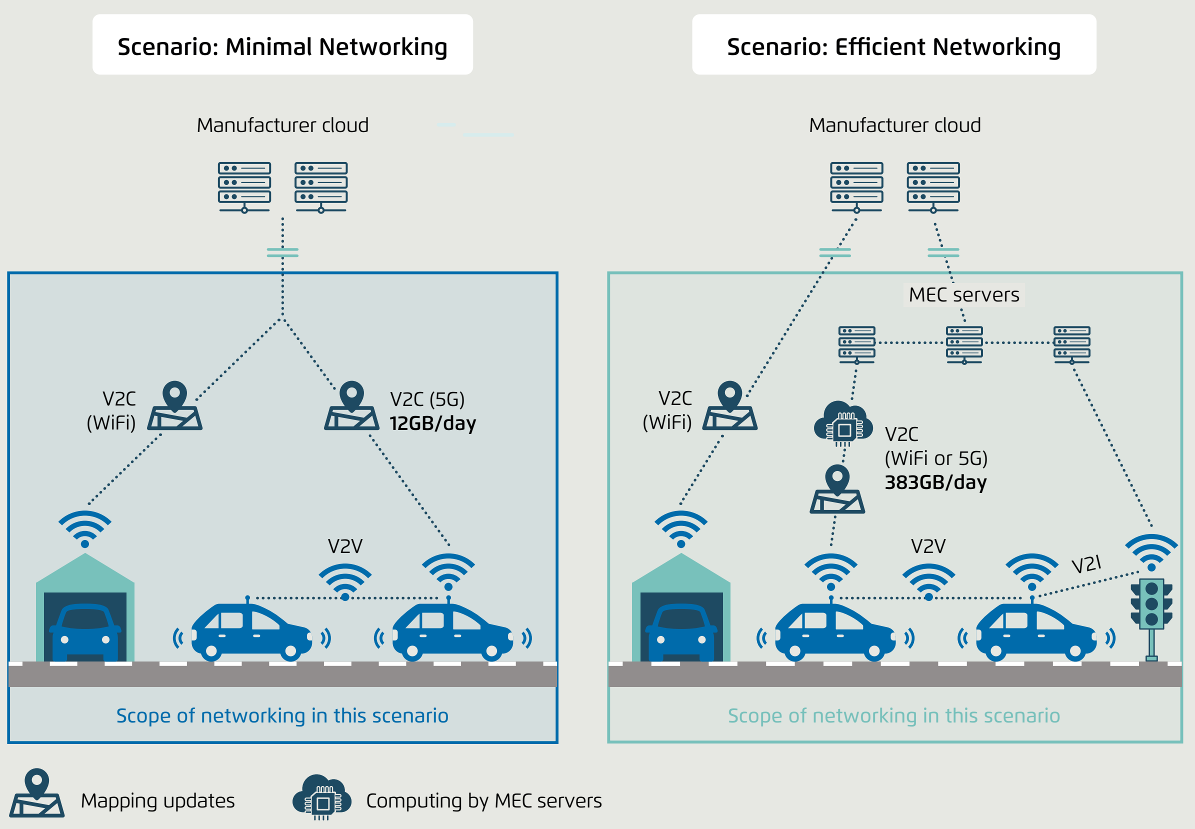
Automation level by year as a percentage of the German vehicle fleet — Figure 1



Adapted from Krail et al. (2019)

Visualizing our automation scenarios

Figure 2



Authors' depiction

3 | The effects of automation and networking on energy consumption

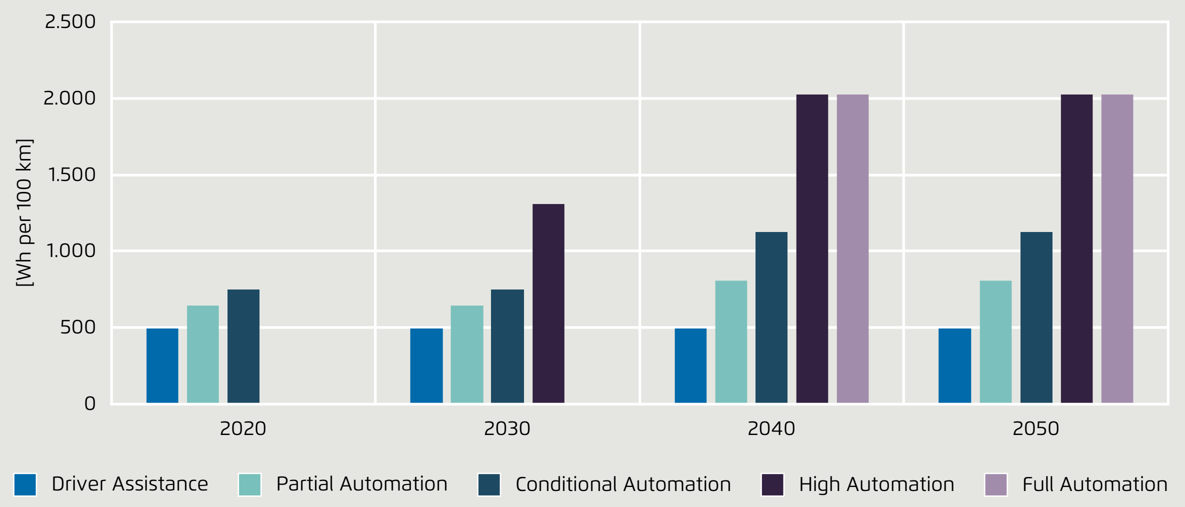
For some years researchers have been studying how connected and autonomous vehicles will impact the transport system, including their effects on greenhouse gas emissions and total energy consumption. Prominent studies in this area include the ITF Lisbon study (OECD/ITF 2015) and the MEGAFON study (Friedrich et al. 2017), both of which examine the effects of a complete switch to a transport system based on connected, autonomous and shared vehicles. Other studies, such as e-mobil-BW (2017), Lee et al. (2019) and Krail et al. (2019) consider the effects that will result for modal shares, carsharing, and associated efficiency gains and losses. Krail et al. (2019) take a particularly close look at efficiency gains. However, virtually all the studies that we surveyed fail to look beyond the confines of the transport sector. In particular, they do not consider the impacts to final energy consumption that could potentially result from cellular-based networking (V2X), from networked road infrastructure (V2I), and from associated backend systems. In this way, efficiency gains in the transport sector could potentially be eroded by increasing final energy consumption outside the transport sector. In order to shed light on the overall impacts that could result at the level of a single vehicle, this study focuses on the following effects:

- CAV effects on the energy efficiency of a vehicle in operation,
- additional onboard final energy consumption by CAV systems,
- CAV effects on the final energy consumption by mobile communications, and
- the effects on final energy consumption of backend systems and networked road infrastructure.

In both scenarios, the difference in final energy consumption per 100 kilometres driven is compared between a single mid-size car with CAV systems and a mid-size car without CAV systems. Our analysis takes into account potential advances in CAV systems over time, in accordance with the scenarios' definition. The following sections describe our approach, underlying assumptions, and results in the aforementioned areas.

Average efficiency potential by automation level

Figure 3



Authors' calculations based on Krail et al. (2019)

3.1 The energy efficiency of driving

Various European field studies, such as euroFOT (Benmimoun et al. 2012), AdaptIVe-IP (Fahrenkrog et al. 2017) and L3Pilot (2020) have examined how automation levels 2 to 4 impact the final energy consumption of passenger cars in real-world settings. Test vehicles from various manufacturers were used to drive several million test kilometres on European roads, and the results were documented and compared with human-controlled vehicles with comparable driving profiles. According to these studies, vehicles with assisted and semi-autonomous driving functionality have a fuel consumption advantage over their human-operated counterparts. Cars with CAV functionality achieve lower fuel consumption predominantly due to improved driving efficiency, including adapted acceleration and braking, optimised engine control, and improved adaption to topography. Additional efficiency advantages compared to non-automated driving could potentially be achieved if it were possible to exceed the upper speed limit 130 km/h (which, on German autobahns, only exists due to sensor range). However, this is not taken into account by the field studies, which merely compare similar driving profiles.

Further efficiency effects stemming from improved traffic flow could be achieved through cooperative driving; these potential effects were not investigated in the field studies, however. Cooperative driving means that individual vehicles and drivers route themselves cooperatively. CAV systems coordinate routing to individual micro-destinations in order to achieve improved macroscopic effects (e. g. such as the more efficient use of infrastructure capacity). However, the networking and automation of almost all road vehicles are required for this efficiency potential to be exploited, and our market growth estimates show that only part of the vehicle fleet will be networked and automated by 2050. Accordingly, we do not devote additional attention to this issue, or seek to quantify its efficiency potentials. In this way, the efficiency potential offered by CAVs in the Minimal Networking scenario is identical to that of the Efficient Networking scenario.

Based on findings from the above-mentioned field studies, Krail et al. (2019) estimate overall efficiency effects for each level of automation up to fully autonomous driving. When the findings from the aforementioned field studies are combined with our analysis, we find that the efficiency potential of connected and automated vehicles depends on numerous factors, including the road type, traffic density, level of automation, and percentage of CAVs in the total vehicle population. Therefore, when calculating representative efficiency potentials based on gathered field data, these factors were taken into account. Figure 2 shows the calculated average energy saving potential for a mid-sized car across all automation levels up to 2050. The increasing number of CAVs on the road up to 2050 will also increase the efficiency potential of standard passenger cars. This is because the number of inefficient driving situations will decrease as the share of human-controlled vehicles shrinks (Krause et al. 2017). Levels 4 and 5 lack a savings potential in 2020 and level 5 lacks a savings potential in 2025 as market-readiness for these automation levels is not expected until 2025 and 2035, respectively.

In both scenarios, a savings potential is evident across all automation levels. It increases from 493 Wh/100 km at level 1 to just over 2,000 Wh/100 km at levels 4 and 5 in 2050. Converted to the consumption of a diesel-based car, this would mean savings of between 0.2 and 0.8 litres per 100 kilometres. However, this savings potential can only be achieved if the available automation functions are actually used whenever possible. Determining the efficiency improvements that can be achieved through autonomous driving requires the gathering of observational data. Accordingly, if fully autonomous driving is not introduced in urban areas until 2035, we will have to wait until that time to quantify overall energy savings effects, e. g. from services such as fully autonomous taxis.

3.2 Energy consumption by on-board automation systems

In addition to the opportunities for increased efficiency offered by connected and autonomous vehicles, one must also consider countervailing effects that reduce efficiency. Important countervailing effects include the direct energy consumption of CAV systems in the vehicle, in addition to higher energy consumption from increased vehicle weight or air resistance (e. g. due to lidar sensors on the roof). We have not taken such aerodynamic effects into account, however, as sensor position does not lead to poorer aerodynamics among all vehicle makes.

In order to estimate the additional consumption of a connected and autonomous vehicle in comparison to a non-connected and non-automated vehicle, estimates must first be made of the number and type of system components installed. In this regard, there are some considerable discrepancies, at least for the level 2 and 3 models available to date. While Tesla relies heavily on cameras, German manufacturers mostly rely on medium and long-range radar, in combination with lidar sensors and cameras. Based on our expert interviews and Krail et al. (2019), we have made assumptions regarding the number and type of system components installed, as documented in Table 1. For highly automated cars (level 3), the number of components corresponds to that of the Audi A8, one of the first level 3 production cars.

Based on this definition, a final energy consumption range has been determined for each required CAV system component. The respective energy consumption range per system component has been taken from Gawron et al. (2018) and Liu et al. (2019). Based on these consumption ranges and our assumptions regarding the number of sensors, cellular units and computer systems required, minimum and maximum energy consumption per car could be estimated per 100 kilometres driven. We then validated the results of this calculation using the information from the qualitative interviews that were conducted with experts from academia and industry. The additional energy consumption resulting from the additional weight of the sensors, cellular units and computer systems was also included in our calculations.

Our estimates are much closer to that of Gawron et al. (2018) and the interviewed experts than to the results of Liu et al. (2019). Variation in the number and type of components installed is the main reason for this divergence. Liu et al. (2019), for example, adds the final energy consumption of TFT monitors in the cockpit. However, such monitors are already being installed in vehicles, even those lacking automation and networking functions. In light of our expert interviews and the stakeholder meetings documented by Krail et al. (2019), we believe the assumptions made in our study are valid.

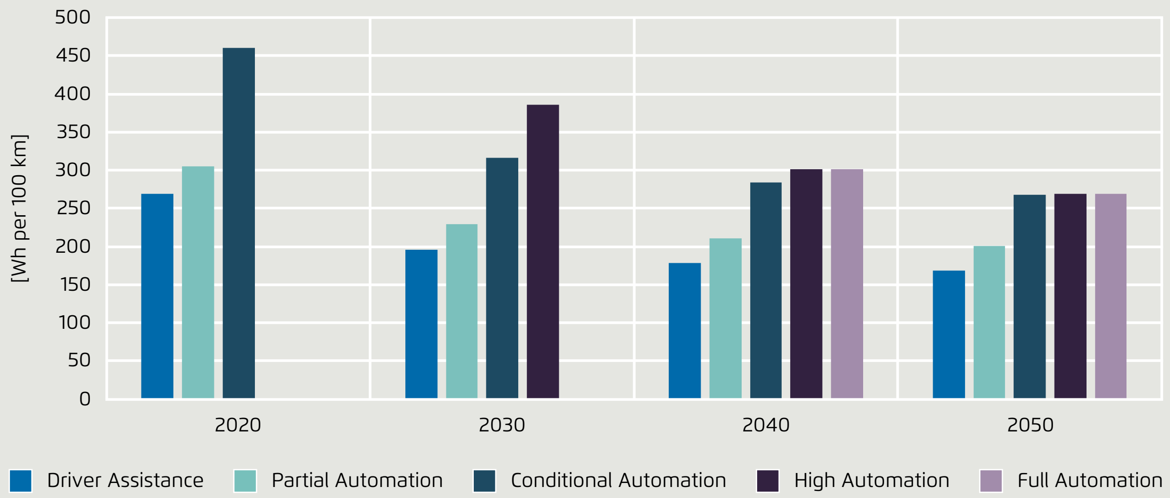
The installed memory and computing units (CPUs and GPUs) are particularly important in terms of final energy consumption. According to Gawron et al. (2018), between 41 and 53 % of additional final energy consumption is attributable to these components. By contrast, cameras and sensors (radar, ultrasound, lidar) only account for between 2 and 7 % of the additional energy consumption of CAV systems. The additional weight of CAV components is responsible for approximately 14 to 15 % of the additional energy consumption. According to calculations we performed based on data from Gawron et al. (2018), a level 3 car currently consumes between 310 and 656 Wh/100 km. From a present-day perspective, a level 4 car would consume between 555 and 800 Wh/100 km of energy. However, we must also consider how the energy efficiency of CAV components might improve due to technological advances up to 2050. To this end, we made assumptions regarding the CAV equipment set at each level of automation (see Table 1) based on the

Assumptions regarding the number of CAV system components per automation level — Table 1

Components	Level 1	Level 2	Level 3	Level 4	Level 5
Ultrasound	9	9	9	9	9
Radar	2	4	4	8	8
Lidar	0	0	1	1	1
Cameras	0	2	5	5	5
DSRC	1	1	1	1	1
GNSS positioning	1	1	1	1	1
V2X module	1	1	1	1	1
Control units	1	1	2	3	3

Fraunhofer ISI (adapted from Krail et al. 2019)

Additional final energy consumption by onboard components for a single vehicle — Figure 4



Authors' calculations based on Krail et al. (2019)

information obtained from the surveyed experts. These equipment sets subsequently served as the basis for our energy consumption calculations for 2030, 2040 and 2050. We presume that the energy efficiency of the components can be improved by 10 % up to 2050. With a view to computing and storage units, our energy efficiency calculations are based on Koomey's law, which states that the energy efficiency of computers, measured in terms of computing power, doubles every 1.57 years – a trend that has held true since 1975 (Koomey et al. 2011). In our study, we assume a more conservative rate of doubling (every 5 years). We also assume an increase in computing power of 20 % every 5 years. Aside from the automation components listed in Table 1, it is conceivable that the installation of a what is known as a drive recorder will be legally mandatory. If the recording of trip data over an extended period of time is legally required, this could further increase onboard energy consumption. However, as the magnitude of this increase will depend on legal data storage requirements, we have not taken this factor into account.

Figure 3 shows the estimated effects of the CAV components on final energy consumption, as measured in Wh/100 km for a mid-sized car. The estimates differ by automation level, due to variance in the equipment sets.

In 2020, the additional energy consumption is estimated at 269 Wh/100 km for level 2 cars and 460 Wh/100 km for level 4 cars. By contrast, for 2050 we estimate additional energy consumption of between 170 for level 2 cars and 270 Wh/100 km for level 5 cars. Converted to the fuel consumption of a diesel passenger car, this would mean an additional consumption of between 0.17 and 0.27 litres/100 km.

3.3 Energy consumption from cellular-based networking

Connected and autonomous vehicles are laden with sensors that generate an enormous volume of data. In CAV test vehicles, data volumes range between 1.4 TB/h and 19 TB/h (see e. g. Heinrich 2017). Intel (2017) posits CAV data volumes of about 5 TB/h. High-resolution digital maps – which can require as much as 1.5 TB of storage space for a single city – are a basic requirement for safe autonomous driving. Furthermore, map material must be regularly updated to account for current conditions. The volume of sensor data generated by a single CAV far exceeds the cost-effective transfer capacities of current cellular technologies (Gatzke et al. 2016). If vehicles were designed to exchange all data with the environment through cellular connectivity, today's cell networks – which are based on the 4G/LTE standard and have a maximum data transfer rate of approx. 300 MB/s – would be overwhelmed. Even the new 5G standard, which enables data transfer rates between 1 and 10 GB/s, would be unable to fully accommodate CAV network traffic. Yet even if the immense volume of data produced by autonomous vehicles could be transferred on a technical level, the question arises as to whether such data transfer would lead to an excessive increase in final energy consumption by cellular-network infrastructure and data centres.

In order to answer this question, we first determined the average final energy consumption by the current cellular network system, including data centres, for a given volume of data. We also performed the same estimates for a nationwide 5G network of the future. According to the estimates produced by cellular network operators (e. g. Vodafone 2019) – estimates that have been confirmed by further studies (e. g. Höfer et al. 2019) – the switch from 4G to 5G will reduce energy consumption from approximately 3.5 Wh per transmitted GB (4G) to 1 Wh per GB (5G). At first glance, this decline appears surprising, because some calculations – such as those performed at RWTH Aachen University (Höfer et al. 2019) – show increasing energy consumption due to 5G. However, these estimates depend significantly on associated assumptions regarding growth in transferred data volumes, which could significantly overshadow per-unit energy efficiency gains. However, based on our calculations, it would appear advisable to take the prior estimate concerning the development of energy efficiency into account. In our calculation of CAV final energy consumption, we assume 100 % conversion to the 5G standard by 2030.

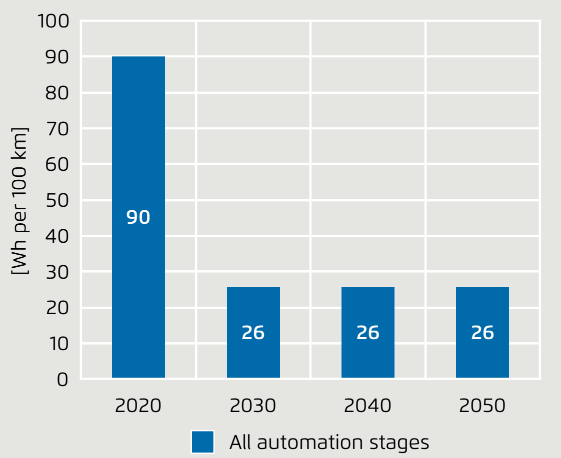
While our networking scenarios do not differ in terms of the energy efficiency potential of vehicles or the additional consumption that will arise onboard due to CAV equipment, we do vary our assumptions with a view to energy consumption by cellular networks. These divergent scenarios are reflective of uncertainty regarding the volume of CAV data that will be processed by cellular networks. Researchers agree that cost-effective data exchange in V2X will only be possible by using big-data analysis techniques (Gatzke et al 2016). However, the secondary literature does not provide a clear picture of the extent to which the data volumes can be reduced using such methods. Therefore, in our Minimal Networking scenario, we assume that data exchange between vehicles is not performed via cellular communication. Instead, vehicles only receive data via cellular network if a mapping update is necessary. However, both the Minimal Networking and Efficient Networking scenarios presume that in normal cases, mapping updates will be downloaded using WiFi prior to the start of a journey. We assume that half of all mapping updates are performed using WiFi. Energy consumption by WiFi repeaters in garages is added to the energy consumption of the backend, which is estimated in section 3.4. With a view to vehicles normally parked on public streets, update by WiFi is only possible in select cases. For such vehicles, we presume that mapping updates are performed in the Minimal Networking scenario by cell network, and in the Efficient Networking scenario by MEC server connectivity. In view of the minimum requirements described above, we assume in the Minimum Networking scenario that just 12 GB per day are transmitted to the vehicle by cell network. This does not seem like an unrealistically low figure, given that other solutions for map updating might emerge. Some OEMs, for example, are currently working with map providers on ways to efficiently update HD maps through vehicle sensors.

The Efficient Networking scenario is informed by different assumptions. Specifically, we assume that networking between vehicles (V2V) and the backend (V2C) can additionally take place through the cell network (e. g. if distances between vehicles prevent use of the IEEE 802.11p standard). However, as the cellular transmission of the CAV data volumes described at the beginning of this section pose technical problems and would not be cost efficient, we assume that data flows are limited to the minimum necessary volumes. The Automotive Edge Computing Consortium (AECC), which is made up of numerous prominent actors in the IT and mobile communication sectors, has developed three possible scenarios for the development of the CAV data volumes (AECC 2020). In the low-range scenario, the amount of data sent through the cellular network is estimated at 0.383 TB per hour per vehicle. The AECC considers this scenario to be the closest to cooperative driving. Therefore, we presume this amount of data transfer when calculating final energy consumption for the cellular network. One assumption in this scenario is that the vehicles do not permanently and completely send all data from sensors to the backend, but rather only in a selected manner.

Figures 4 and 5 show the additional final energy consumption that would result from data transmission in the cellular network given the assumptions in the Minimal Networking and Efficient Networking scenarios. The decline in energy consumption up to 2050 is the result of conversion to 5G technology. While the assumptions contained in the Minimum Networking scenario lead to a marginal increase in final energy consumption of 26 Wh per 100 km in 2050, the larger data flows that occur in the Efficient Networking scenario cause a noticeable increase in final energy consumption of 766 Wh per 100 kilometres.

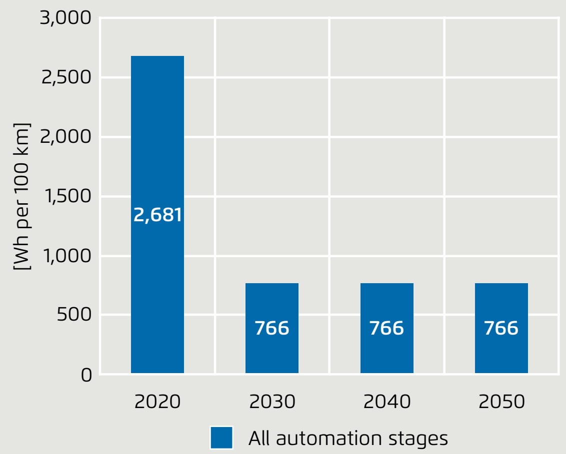
If big-data analysis methods are not used in the future to optimise network data volumes, the additional energy consumption that would result could devour the energy efficiency gains outlined in section 3.1. Indeed, the countervailing increase in energy consumption associated with data exchange offsets the described efficiency gains at data exchange rates of 0.8 TB per hour (or higher). Given the mid-range scenario developed by the AECC (2020), which assumes an even higher volume of data exchange, the overall energy scorecard of connected and autonomous vehicles is negative rather than positive.

Final energy consumption by V2X in mobile communications – Minimum Networking scenario — Figure 5



Calculations by Fraunhofer ISI

Final energy consumption by V2X in cellular networks – Efficient Networking scenario — Figure 6



Calculations by Fraunhofer ISI

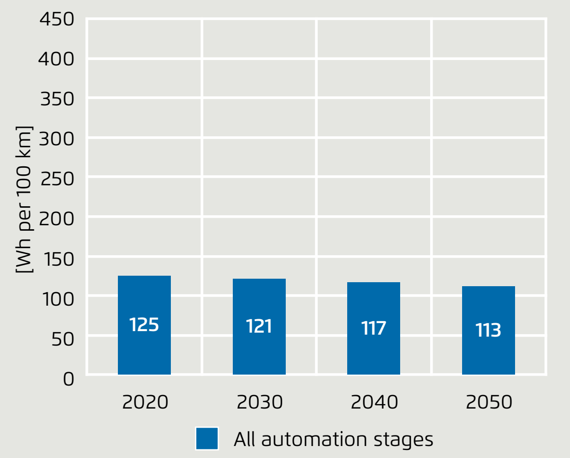
3.4 Energy consumption by the backend

Manufacturers are designing passenger cars with autonomous driving features to be safe in all usage scenarios, even given the absence of a backend system that is used to manage autonomous vehicles. In our Minimum Networking scenario, we assume no continuous communication with a backend system. Accordingly, no additional energy consumption arises in this area per kilometre driven. The only additional energy consumption generated by the backend in the Minimal Networking and Efficient Networking scenarios is attributable to WiFi repeaters, which are used by 50 % of the vehicles to upload current HD maps before the start of a journey. Given a maximum annual energy consumption by these repeaters of 35 kWh (Stiftung Warentest 2018), approx. 125 Wh of additional energy consumption will arise per CAV and 100 km driven in 2020. Assuming that the energy efficiency of these repeaters improves by 10 per cent, final energy consumption will decline to 112 Wh per 100 km by 2050 (see Figure 6).

In the Efficient Networking scenario, we assume that vehicle networking (V2V) and backend/cloud networking (V2C) and infrastructure networking (V2I) can be largely

Final energy consumption by the backend – Minimal Networking scenario

Figure 7



Calculations by Fraunhofer ISI

realised by 2050. In this scenario, communication with the backend is achieved through decentralised MEC servers, using either 5G connectivity or the 802.11p standard. The MEC servers can be used to transfer various types of data to and from the vehicles, including information on traffic events, HD map updates, or other data from manufacturer-specific databases. The decisive advantage of MEC is short latency times, which cannot be realised with a centralised cloud/backend solution.

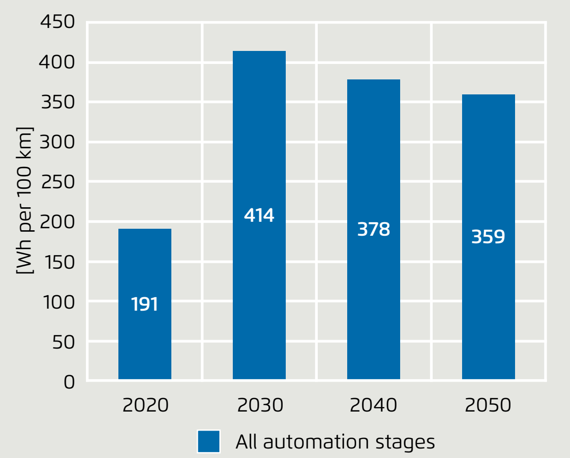
Our assumptions regarding MEC coverage of the German road network were previously detailed in section 2. In order to estimate final energy consumption by MEC infrastructure, we draw on the requirements cited by experts in the qualitative interviews. In areas with MEC coverage, a base station is set up at 20 kilometre intervals. Section 2 describes our assumptions regarding coverage by road type; we assume 2,930 MECs will be installed by 2050. A base station consists of three computers with annual electricity consumption of 780 kWh each (our calculations are based on BMWi 2020). Each base station also features a transmitter module with annual electricity consumption of 88 kWh. Our assumptions regarding improvements in the energy efficiency of computers – as detailed in section 3.2 – imply a reduction in the annual energy consumption of each computer to 245 kWh in 2050.

In addition to networking with the backend, the Efficient Networking scenario assumes the partial networking of road infrastructure. However, we assume that networking is limited to traffic signals and signs relevant to connected and autonomous vehicles. This V2I infrastructure will be equipped with cellular modules to supply information to approaching vehicles. We calculate the final energy consumption of networked road infrastructure by drawing on the work of Liu et al. (2019). Each networked sign or signal increases final energy consumption by approx. 88 kWh per year. There are no official statistics on the number of traffic signals and road signs in Germany. Experts estimate that there are approximately 50,000 to 60,000 traffic signals and 20 million road signs. Our Efficient Networking scenario assumes that by 2050, all traffic signals and 6 million road signs will have been networked.

After combining the additional energy consumption attributable to the backend and networked road infrastructure, we extrapolate the energy consumption attributable to one vehicle driven 100 km based our estimates for level 2 to 5 CAV penetration rates (see Figure 1). In this connection, we assume each vehicle is driven 14,000 kilometres per year on average. This yields the final energy consumption attributable to the backend and networked road infrastructure shown in Figure 6. Per 100 kilometres driven, energy consumption ranges between 191 Wh in 2020 to 359 Wh in 2050 (see Figure 7).

Final energy consumption by the backend – Efficient Networking scenario

Figure 8



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3.5 Overall effects on energy consumption

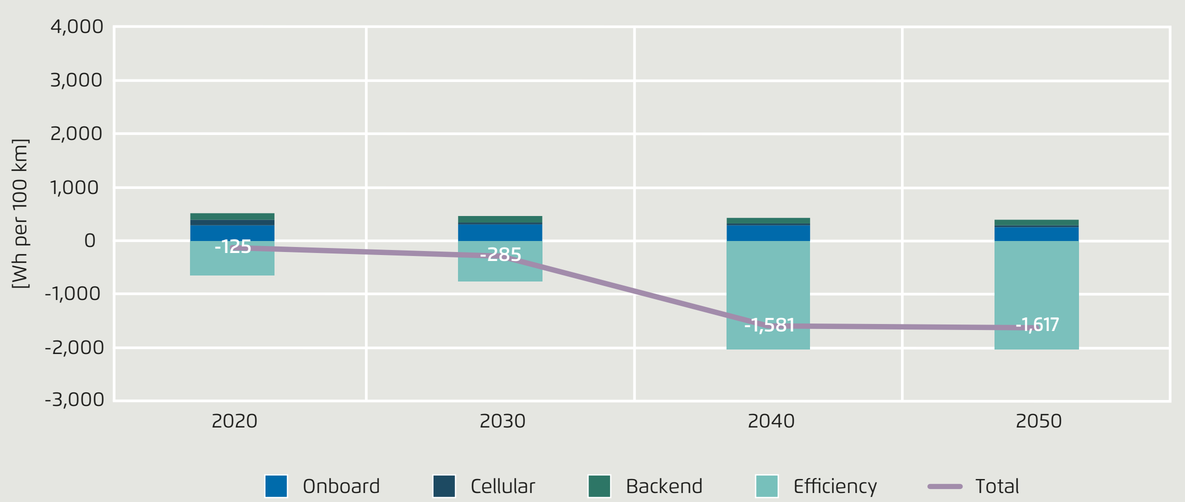
In the previous four subsections, we described our assumptions and associated calculations regarding the energy consumption impacts of connected and autonomous driving in relation to a single vehicle. Sections 3.1 and 3.2 described divergence in energy consumption by the vehicle itself – on the one hand, energy savings due to more efficient driving performance, and, on the other hand, additional energy consumption due to onboard automation and networking equipment.

However, as this study aims to consider the net total change in energy consumption that can be expected with the adoption of connected and autonomous vehicles, in the following we also present the cumulative net change in energy consumption per vehicle and 100 kilometres driven. The overall impact of connected and autonomous vehicles on final energy consumption per 100 kilometres driven is detailed in Figure 8 for the Minimal Networking scenario and in Figure 9 for the Efficient Networking scenario.

While the energy efficiency gains and additional consumption caused by onboard CAV systems depend on the automation level of the vehicle, energy consumption by the cell network and backend is almost invariant, regardless of the level of automation. Accordingly, for the sake of simplicity, figures 8 and 9 are not broken down any further by automation level. We consider the highest available level of automation in each respective year when estimating CAV efficiency gains and additional energy consumption by onboard systems. Specifically, the estimations for 2020 based on level 2 automation; 2030 is based on level 3; 2040 is based on level 4; and 2050 is based on level 5.

As the additional final energy consumption attributable to cellular communications impacts the net consumption figures from the very beginning – that is, from 2020 onward – the two scenarios diverge in crucial respects. While modest energy savings of 125 Wh/100km are achieved in the Minimal Networking scenario from the very beginning, the Efficient Networking scenario initially leads to substantial additional consumption of 2,500 Wh/100km. Indeed, the energy savings achieved in the Efficient Networking scenario are overshadowed by the higher energy consumption of cellular networking up to 2030. In this way, the Efficient Networking scenario's strongly positive effects on final energy consumption only become apparent after 2030. In the long

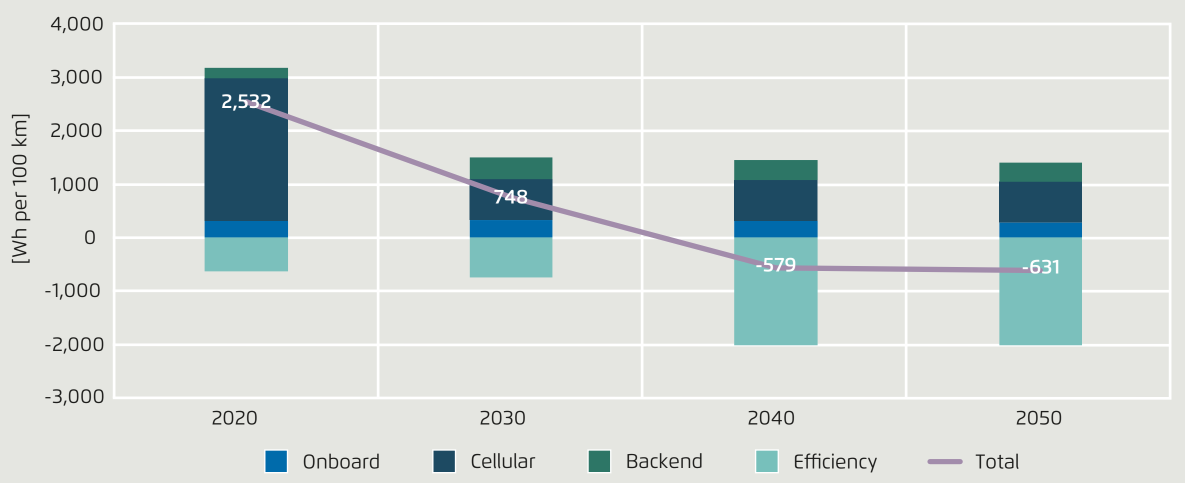
Change in net energy consumption of mid-sized CAV – Minimal Networking scenario | Figure 9



Calculations by Fraunhofer ISI

Change in net energy consumption of mid-sized CAV – Efficient Networking scenario

Figure 10



Calculations by Fraunhofer ISI

term, both scenarios show a substantial energy savings potential of between 631 and 1,617 Wh per 100 km. If one calculates the cumulative annual impact of CAVs on energy consumption up to 2050, both scenarios are associated with lower energy consumption than a fictitious scenario without CAVs. Specifically, a cumulative total of 38 TWh is saved up to 2050 in the Minimum Networking scenario, and a total 6 TWh is saved up to 2050 in the Efficient Networking scenario.

3.6 Potential rebound effects

Some studies refer to connected and autonomous vehicles as a disruptive technology beginning at level 4, as this level of vehicle autonomy promises to enable completely new forms of shared mobility. As an enabler of convenient door-to-door transport, level 4 autonomous vehicles could become a cost-effective alternative to traditional public transport networks (Bösch et al. 2017). Furthermore, level 4 vehicles would allow drivers to spend travel time concentrating on other activities. Lastly, there is the hope that CAVs will decrease driving times thanks to optimised routing and the improved utilisation of road infrastructure. However, numerous studies warn that by improving the convenience and efficiency of passenger vehicles, CAVs could lead to undesired rebound effects, including in particular a higher modal share for road transport. However, there is disagreement in the literature as to the magnitude of the rebound effect that can be expected. While e-mobilBW (2017) and Taiebat et al. (2019) predict significant changes in the modal share due to CAVs, Krail et al. (2019) anticipate noticeable but smaller changes. Ultimately, these authors come to different conclusions because of alternating assumptions regarding the timeline for autonomous vehicle adoption. Krail et al. (2019) assume that for cost reasons, only a small- to medium-sized share of the vehicle fleet will be equipped with level 4 and 5 automation functions by 2050. As a result, Krail et al. do not envision the materialisation of the benefits assumed in other studies, such as the improved utilisation of road infrastructure and reduced travel times. Krause et al. (2017), by contrast, believe that these benefits could be attained by a mixed vehicle fleet consisting of autonomous and human-driven vehicles. In any event, connected and autonomous passenger vehicles are likely to become increasingly attractive to consumers moving forward. At the same time, public transport authorities have been examining how to make their systems automated and networked, in order to offer their customers more flexible and cost-effective solutions.

We conclude that in the aggregate, between 1.2 and 3.2 TWh of final energy consumption can be saved before 2050 through the adoption of CAVs. Assuming that the total energy consumption of passenger vehicles is reduced to about 120 TWh by 2050 – as envisioned in the long-term scenarios of BMWi (2017) – the net efficiency gain of CAVs would still be positive if the annual distance driven by passenger vehicles were to increase by 1 to 2.6 %. Stronger rebound effects would entail a net increase in total final energy consumption.

However, apart from undesired rebound effects, it should also be mentioned that, in addition to the energy saving potentials described above, connected and autonomous vehicle technologies provide numerous opportunities for catalysing the transition to a sustainable transport system. Given a tailored regulatory and policy environment, CAV technology could encourage people to flexibly combine modes of transport in a manner that reduces energy consumption. Shared mobility services that rely on automation and networking may be the missing piece of the puzzle that would make private vehicle ownership unnecessary. Insofar as CAV promotes greater reliance on shared mobility solutions, it could represent an important cornerstone of the climate-friendly, sustainable transport system of the future.

4 | Recommendations for action and outlook

Our evaluation of the effects of connected and automated vehicles up to 2050 has shown that CAVs can improve the energy scorecard of the entire transport system, despite the additional energy demand entailed by cellular networking and backend operation. However, in order to ensure a net negative impact on energy consumption, a number of conditions must be fulfilled.

The energy efficiency potential of CAVs can be further improved by cooperative driving and the resulting optimisation of traffic flow. However, this potential can only be exploited if suitable networking technologies are in place, which will require cooperation between manufacturers. In this connection, a fundamental requirement is the development of a backend for autonomous vehicle communications, in addition to the establishment of networked road infrastructure. Policy-makers have a choice between two options: they can directly make the investments necessary or they can coax industry to make them with policy instruments.

Manufacturers and suppliers should continue to work on improving the energy efficiency of onboard sensors and control units. While demands on onboard computer performance are sure to rise in the future, efforts should be made to avoid associated increases in energy consumption. In this regard, manufacturers need to collaborate with suppliers to promote the development of energy-efficient components, especially in the area of processors and data storage. Given the importance of range for battery electric vehicles, optimizing the energy efficiency of components is a crucial building block in the broader transition to sustainable transport.

In the domain of software, as well, solutions for the efficient handling of large data volumes must be found by car manufacturers, component suppliers and IT service providers. The development of efficient big-data analysis methods will be essential for gathering CAV sensor data to improve road safety and optimise traffic flow, without negative effects on final energy consumption.

Ultimately, a key aim is to keep unwanted rebound effects to a minimum and to realise desired synergies. To this end, public authorities must develop tailored regulations for the operation of connected and autonomous vehicles. If empty vehicle operation is permitted, it should, at a minimum, be made economically unattractive. It will also be important to find a compromise solution that enables Mobility as a Service (MaaS) for shared and pooled journeys, without excessively reducing reliance on public transport. In this context, it is also important to support public transport authorities in their efforts to develop and deploy flexible, automated and networked systems, in order to ensure competitiveness with MaaS.

The recommendations for action enumerated above could naturally be applied to a well-established system of 100 % autonomous vehicles. However, the road to comprehensive automation is a long one, not only due to the high cost of automation technologies for consumers, but also given the unresolved technical hurdles to negotiating complex traffic environments.

5 | Literature

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In partnership with key players in the field of politics, economics, science and civil society, Agora Verkehrswende aims to lay the necessary foundations for a comprehensive climate protection strategy for the German transport sector, with the ultimate goal of complete decarbonisation by 2050. For this purpose we elaborate the knowledge base of climate protection strategies and support their implementation.

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