Automation-driven transformation of road infrastructure: a multi-perspective case study

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Abstract

Automated driving is widely assumed to play a major role in future mobility. In this paper, we focus on “high driving automation” (SAE level 4) and analyze potentials in terms of more efficient traffic flows, travel times, and user benefits as well as potential impacts on urban neighborhoods and potentials for sustainable urban development. Along selected use cases of automated vehicles in the region of Karlsruhe, Germany, we show that at least moderate user benefits can be expected from travel time savings, with the extent depending on the defined operational design domain of the vehicles and the routes taken. With regard to residential development of urban neighborhoods, there are opportunities for repurposing public space. However, these are limited and require parallel regulatory measures to become effective.

1 Introduction

It is widely assumed that automated driving will be an integral part of future mobility and that it may have significant impacts on the mobility sector, urban planning, and land-use patterns. With recent developments in vehicle sensors and telecommunications, cooperation between vehicles and supporting information infrastructure promises increased efficiency of traffic management as well as improvements in road safety. New on-demand services could contribute to reducing vehicle ownership and thus alleviate the tight parking situation in densely populated urban areas (Fraedrich et al., 2015; International

Transport Forum [ITF], 2017; Lenz & Fraedrich, 2015; Litman, 2018). Assuming that regulation of road transport automation contains induced travel demand and vehicle mileage, automated vehicles [AVs] could represent a genuine improvement for future mobility. On the other hand, problems might arise when road transport automation fails to meet urban transport planning objectives, such as avoiding urban sprawl or enhancing the conditions for non-motorized and public transport – with problems exacerbated by support for the new technology (Fraedrich et al., 2015; J. Meyer et al., 2017).

Use cases and impacts of automated cars strongly depend on the level of automation the cars are assumed to reach and, correspondingly, which interactions in the socio-technical mobility system can or should be expected. In general, different levels of automation are distinguished, ranging from already established driver assistance technologies to fully automated cars that can handle all traffic situations without a driver. The Society of Automotive Engineers International defines five levels of vehicle automation (SAE International, 2018). At levels 1 and 2, the human driver still monitors the driving environment and is assisted by various types and combinations of driver assistance systems. At levels 3 to 5, an automated driving system monitors the environment. At level 3 [L3], the human driver is expected to respond appropriately to a request to intervene. At level 4 [L4], the vehicle operates autonomously in predefined contexts and the human driver is not expected to respond immediately to a request to intervene. Only level 5 [L5] enables full driving automation: at this level, the automated driving system provides full-time performance under all roadway and environmental conditions that a human driver could handle. Many of the abovementioned visions and impacts refer to driverless cars that correspond more or less to L5 in the SAE nomenclature.

There are rather different opinions on the question of when and in which spatial contexts the realization of the different levels of automation can be expected (Fraedrich et al., 2015). One thread of discussion expects an evolutionary pathway, assuming a continuous extension of the degree of automation over time, passing through all levels and finally reaching L5. Others argue that a revolutionary pathway may be possible as well, assuming that driverless L4 or L5 taxi services will be commercialized soon and become widespread over time.

In this paper, we take a deeper look at the diffusion of L4 vehicles that have a general capability to perform all driving tasks but have this capability limited to a specific operational design domain [ODD]. We do this because both pathways illustrated above imply the emergence (and thus relevance) of L4 in one way or another at some point of time, earlier than the technologically most challenging L5: In an evolutionary pathway, L4 vehicles could expect the driver to take over the driving task (handover) no longer dynamically (as at L3) but only when leaving the respective ODD. By contrast, also in a revolutionary pathway, applications such as driverless taxis could, e.g., be restricted to specific ODDs and thus fall under the L4 category. In terms of concrete traffic situations, we see two fundamentally different entry points for vehicle automation where limited ODDs for L4 vehicles could be defined: First, L4 capabilities could include highways or similar road types, with high speeds and low complexity; second, L4 capabilities could address urban areas, with low speeds but high complexity. Yet, beyond technological achievements, a high degree of attractiveness of L4 vehicles is necessary to make their commercialization likely – so that the vehicles will actually be purchased or operated in shared schemes and have an impact on the mobility system. Therefore, we focus on potential ODDs that are useful for people and their actual travel needs. This, in turn, leads to use cases including handover situations, where users can combine their vehicles' L4 capabilities with driving themselves outside of the L4 ODD. We are interested in the concrete benefits that such use cases may bring compared to existing car mobility.

However, following this reasoning, there is still a wide variety of potential use cases. We therefore restrict our analysis to a very distinct and clearly defined case that allows us to analyze potential benefits in a very concrete manner. We present a case study for the German region of Karlsruhe analyzing different aspects of L4 automated driving. Building on a typical commuter's routine, travelling between a rural village and a specific urban district, the overall aim of the paper is to bring together different disciplinary perspectives and thereby uncover and discuss their interrelations and resulting challenges. This allows us to put together a consistent analysis of a number of areas where the potential benefits of this specific L4 use case may arise, including both potential direct benefits to the user and potential benefits to the urban environment. The following questions are addressed:

- What are the impacts of using specific L4 vehicles on traffic flows and travel times?
- What are the travel time related monetized user benefits of using specific L4 vehicles?
- What is the potential for sustainable residential neighborhood development, building on the impacts of L4-based traffic reorganization?
- Where can synergies between transport, economic, and residential goals related to the use of specific L4 vehicles be identified, and what potential effects or challenges may lead to conflicts or tradeoffs?

The paper is structured as follows: After introducing the ODD considerations framing the case study, the details of the case study are presented. Then, based on the case study, the impacts on traffic flows and travel times as well as user benefits for commuters are estimated. Finally, the paper elaborates the development prospects of an urban district in an L4 automation environment. The paper closes with a discussion and conclusions, addressing synergies and potential conflicts.

2 Operational design domains for L4 vehicles

In our work, we refer to the definition of vehicle automation by SAE International (2018), which clarifies the roles of the human and the automated driver. We therefore distinguish between the execution of steering in longitudinal and lateral directions, the responsibility to monitor the driving environment and perform a dynamic driving task, and the ODD.

L4, or "high driving automation," the focus of our study, is described in SAE International (2018, p. 19): "The sustained and ODD-specific performance by an ADS [automated driving system] of the entire DDT [dynamic driving task] and DDT fallback without any expectation that a user will respond to a request to intervene". In contrast to L5, or "full driving automation," this description does not apply to all driving modes but only to specific ones. However, there is a broad range of different situations or areas where L4 could conceivably be applied. Several real-world characteristics of roads and their environments – and how L4 vehicles are able to handle them, respectively – define the potential limitations of different possible ODDs (see Table 2.1). These characteristics include, e.g., speed levels, weather conditions, and in particular the complexity of interactions with other road users. The latter covers types of intersections and the presence (or absence) of vulnerable road users such as cyclists and pedestrians.

A frequently expressed expectation is that automated driving will first be introduced on freeways (high speeds/low complexity, see above). This perspective can be extended step by step to other ODDs, e.g., to include intersections with clearly regulated priorities or conventionally signaled intersections. Implicitly, different technical capabilities of the respective L4 vehicles must be assumed, e.g., safe detection of traffic lights even under adverse lighting conditions. Interactions with other road users (particularly cyclists and pedestrians) further complicate the possibilities. For example, a use case of L4 vehicles can be imagined where these are capable of driving on all roads where (1) cyclists do have physically separated lanes or at least dedicated lanes and (2) sufficient sidewalks exist throughout – but vehicles would then also need to be able to handle interactions (e.g. yielding) at intersections as well as undefined locations.

A second expectation is that widespread application of automated driving could also start at low speeds. In this perspective (low speeds/high complexity, see above), the lower speeds are expected to allow for safe and timely reactions in the complex situations of daily city traffic, particularly in interactions with cyclists and pedestrians, while higher speeds on main roads would still require the driver. This strand of expectation is particularly related to discussions about the reorganization of urban spaces, such as the radical reduction of on-street parking.

In any case, the specific use cases of L4 vehicles, following different possible ODDs, raise various follow-up questions. We assume that a wide range of use cases are plausible from a technical and legal perspective, but the consequences for the driving experience, the interaction with other road users, or the urban surroundings and the design of urban infrastructures as well as roads may differ significantly. Our case study will shed some light on a selection of these aspects.

Table 2.1: Typical occurrences of traffic environments in the German road network setting the framework for potential L4 ODDs

Road type	Typical speed limit	Intersections	Cycling infrastructure	Pedestrian access
Freeway	>50 km/h	n/a	none (cycling prohibited)	no
Limited-access road	>50 km/h	grade-separated, yield/stop, signal-controlled	none (cycling prohibited)	no
Main road	50 km/h	yield/stop, signal-controlled	protected/mandatory/ advisory bicycle lane, or mixed traffic	yes (regulated)
Local access road	30 km/h	priority to the right	mixed traffic*	yes (regulated)
Shared space	20 km/h	(priority to the right)	mixed traffic	yes

Note: Despite seemingly clear delimitations, there are diverse site-specific idiosyncrasies (often historical) that make actual ODD definitions particularly complex, including, e.g., left-running single-track tram lines or divided highways with bicycle lanes crossing on-/off-ramps.

3 Case study description

In our case study, we illustrate the potential effects of some of the potential L4 use cases outlined above along a typical commuting trip. Specifically, we look at a car commute of about 20 km from the rural village of Graben-Neudorf to the city of Karlsruhe's "Oststadt" district. With 68% of commuters in Germany relying on cars for their daily commute (Statistisches Bundesamt [Destatis], 2016), the commuting situation is very common and highly relevant in terms of the impacts of the transport system both on people's lives and on the urban and natural environment. In order to analyze how L4 automation may change some of these impacts, we assume a use case built on the following ODD: Combining the two entry points outlined in the previous section, we assume L4 technology that enables automated driving (a) on roads with limited access (no bicycle and pedestrian access) but including at-grade intersections (yield/stop or signal-controlled), and (b) for navigating dedicated areas at slow speeds (including yielding and other interactions with vulnerable road users).

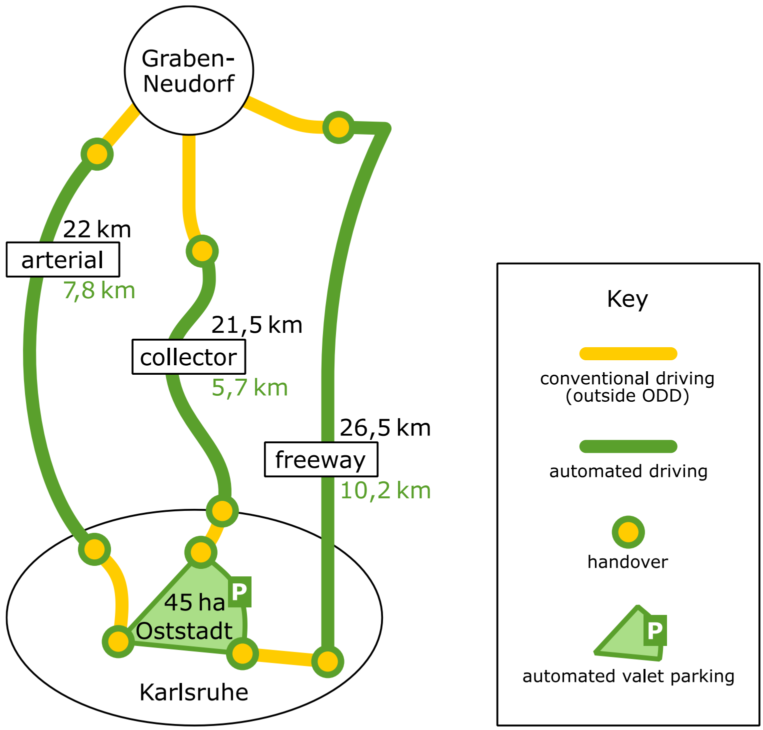

Figure 3.1: Three commuting routes from Graben-Neudorf to Karlsruhe's "Oststadt" district (not to scale)

We do not include normal city traffic in the ODD, since we expect that automation technology (at least in earlier stages of development) may require a stricter separation between modes (e.g., dedicated lanes, less space for pedestrians), which would clearly run counter to current transport and urban planning priorities and policies. Particularly in urban areas, there is a focus on including innovative vehicle technology as just one piece of the mobility transition puzzle, combined with supporting cycling, walking, and public transport. Such integrated approaches suggest considering L4 use cases that could potentially be integrated in a consistent way.

For a car commute from Graben-Neudorf to the Oststadt, three reasonable routes are available (see Figure 3.1): via a collector road ("Landesstraße," shortest route), via an arterial road ("Bundesstraße," often congested during rush hour), and via the freeway ("Autobahn," longest route, but highest speeds when not congested). In terms of the ODD considered in the case, these differ, e.g., regarding handover locations and length of the resulting stretches meeting the ODD requirements, mostly outside city traffic where the vehicles continue to be driven manually. For the collector route, a specific assumption is made for a stretch where cycling is currently not formally restricted: We recognize that restricting this access might be controversial but could be facilitated, e.g., by ongoing parallel discussions about a future bicycle highway in the respective corridor (Spitz, 2019). Furthermore, a number of intersections with rural roads with bicycle and pedestrian traffic would require physical separation that currently does not exist. At the Oststadt destination, we consider an area of approximately 45 hectares as a dedicated zone for automated valet parking in a centralized parking facility.

The purpose of this case study is to make a reasonable selection of L4 automation effects to be analyzed, being aware that there are many other conceivable aspects, side effects, etc. beyond the scope of our interdisciplinary work. Focusing on our common L4 case introduced above, this reduction is what allows our analyses to be directly related to each other (see introduction): analyzing the three routes provides a better understanding of L4 effects on traffic flows and travel times. Together with the time gained by automated valet parking at the destination, these time-related results provide material to assess travel time related user benefits. This is combined with an analysis of the potentials for redesigning public space at the district level and reducing current negative effects of on-street parking, also enabled by the centralized parking system.

A range of important limitations and potential adverse side effects (e.g., discussion of potential conflicts between AVs and other road users in the case of an extended ODD including main roads, or potential urban sprawl induced by more convenient commuting already with a limited ODD) are addressed in the discussion.

4 Effects on traffic flow and travel times

4.1 Methodology

From the perspective of traffic flow modeling, automation of the car commute described above can be divided into three levels: strategic level (departure time choice), tactical level (route planning) and operational level (driving behavior). In this section, we focus on the operational level by means of estimating the impacts of advanced driver assistance systems taking control over the driving tasks, commonly divided into car-following, lane-changing and gap-acceptance tasks. Altering driving behavior with regard to each of these behavioral tasks has a direct impact on the characteristics of traffic flow and subsequently on travel speeds and travel times. The methods to quantify these impacts and provide estimations of the magnitude of travel time changes are typically represented by macroscopic (or in other words, analytical) and microscopic, simulation-based techniques. The former technique is used for uninterrupted, access-restricted network facilities (freeways, grade-separated arterials) where established relations between traffic flow and travel time provide a solid basis for assumption-based modifications of the traffic flow relationships. The latter technique is suitable for interrupted network facilities (urban roads) where interactions between all street-level actors and heterogenous infrastructure elements favor a simulation-based approach. Simulation, when controlled properly, enables the generation of large amounts of synthetic data, capturing variation within the system by randomizing simulation inputs.

Following the methodology described in the previous paragraph, the three commuting routes shown in Figure 3.1 are divided into a sequence of road segments, intersections, and a parking area at the destination. To assess the travel time impacts on the commuter relation, we use the concept of generalized costs where the total travel time costs are split into component costs, differentiated by types of infrastructure. We sum up the impacts on traffic flow for representative uninterrupted/basic road segments (macroscopic), signalized and unsignalized intersections (simulation-based), as well as the costs of cruising for parking within a residential neighborhood (simulation-based). The following paragraphs give a short rationale to each component's travel time estimation and refer to the detailed description by Szimba and Hartmann (2020).

4.2 Results

4.2.1 Freeway Segments

In literature, there are conflicting views on the performance of AVs on uninterrupted freeway facilities. On the one hand, purely analytical approaches showed that in theory shorter time headways between vehicles should provide major capacity increases (B. Friedrich, 2015; Shladover et al., 2012). On the other hand, more complex approaches showed that vehicles equipped with adaptive cruise control (ACC) or cooperative ACC follow gaps that are largely comparable to human-driven time headways (for comfort and safety reasons) (Makridis et al., 2018). This can even lead to a decrease in capacity for certain penetration rates of Avs in the fleet mix (Calvert et al., 2017; Krause et al., 2017). Finally, detailed simulation-based analyses showed that operational aspects of traffic flow such as organization including lane changing, work-zone approach, or speed harmonization must be considered to provide a good and reliable estimation of travel time impacts of automation.

To overcome the need for detailed simulation in high-level planning applications, recent studies integrating Avs into macroscopic traffic demand models (CoEXist, 2020; M. Friedrich et al., 2019; Tympakianaki et al., 2020) proposed modeling of AV impacts by adjusting the passenger car unit factor. In this approach, the standard volume-delay functions such as the function proposed by the Bureau of Public Roads [BPR] (1964) are modified by expressing the impact of Avs by either fixed or volume-dependent passenger car units.

In this paper we refer to the results of Szimba and Hartmann (2020) who estimated the impact of Avs on travel time for uninterrupted freeway facilities by following the macroscopic approach. The estimated travel time savings stem from a nominal increase of freeway capacity using a relationship described by a BPR function and are given for the entire volume-to-capacity range.

4.2.2 At-grade intersections

Unlike uninterrupted facilities that provide sufficient residual capacity to accommodate traffic demand, urban facilities become saturated when the following condition is met: the intersection approach capacity, determined by effective green (signalized intersections) or by gap seeking in the lower-ranked road (unsignalized intersections), is reached. Considering future options, particularly regarding signalized intersections, connecting all traffic to an intersection agent could enable a more systematic approach to traffic management. As a result, higher discharge flows and therefore increased capacity of interrupted facilities could be reached. Vehicle sensors and infrastructure supporting devices act as the main enablers in such a future system, primarily controlling the longitudinal behavior of vehicles. According to Treiber and Kesting (2014), equipped Avs can drive in consolidated flow, which means higher densities near capacity bottlenecks.

In literature, two general approaches to incorporating Avs into traffic flow management at intersections are described: The first approach is based on maintaining conventional traffic flow management (such as by signal groups and intergreen times) and including Avs through reducing queue discharge headways (B. Friedrich, 2015; Lioris et al., 2017). The second approach focuses on autonomous intersection management [AIM], sometimes referred to as a reservation-based intersection control, which departs from conventional traffic signal design and introduces a multi-agent framework for managing Avs at intersections. In this work, we apply the first research approach but refer to the works of Au et al. (2014), Guler et al. (2014) or Yang et al. (2016) on using connected vehicle technology to improve intersection efficiency by means of AIM.

Table 4.1: Capacity increase at signalized intersections (Szimba & Hartmann, 2020)

Car following behavior	**Mean saturation headway [s]**	**Saturation flow [vph]**	**Discharge flow [vph]**	**Capacity Increase [%]**
Human	1.88	1,915	681	-
Cautious AV	1.24	2,900	1,031	51
Assertive AV	1.03	3,495	1,245	83

According to B. Friedrich's (2015) mathematical formulation of AV saturation flows, a 100% AV penetration rate of vehicles organized in platoons can increase the capacity of a signalized intersection approach by 40%. In their experiment, Lioris et al. (2017) even claim a capacity increase by a factor of two to three. In contrast, the ATKINS (2017) report states that the relative benefits of higher AV penetration are not that evident within the urban road network since traffic does not exceed speeds of 30 mph. To consider these results with regard to the case study, Szimba and Hartmann (2020) investigated mean saturation headways at a signalized intersection for different AV driving behaviors. The results are summarized in Table 4.1: Capacity increase at signalized intersections (Szimba & Hartmann, 2020) The ability of Avs to maintain shorter headways translates into a 51 to 83% increase in capacity under the assumption of cautious and assertive driving behavior, respectively.

We note that in the investigated scenario, the acceleration/deceleration characteristics of Avs are not restricted. The findings of Le Vine et al. (2015) suggest that there is a trade-off between capacity increase and passenger-comfort, especially when considering restrictions in the dynamics of Avs. This trade-off is greater when passengers demand the driving behavior of Avs to correspond to the dynamics experienced in rail transport. Further research is also needed to consider the impacts of vibration and oscillation on ride quality, given their importance to the ability of passengers to perform certain types of leisure or productive activities.

4.2.3 Neighborhood

Urban structure creates an important basis for mobility decisions of households and businesses and determines which forms of mobility are enabled or excluded (Heinrichs, 2015). The potential of Avs to transform urban mobility through their on-demand accessibility and facilitated valet parking is therefore high. One of the most profound scenarios of an AV revolution is a neighborhood free of on-street parking where all parking demand is served by either shared automated buses or privately owned Avs autonomously navigating to a central parking garage. In our case study, we investigate the travel time effects of substituting conventional cruising for parking by automated valet parking using the example of Karlsruhe's Oststadt district.

Szimba and Hartmann (2020) used microscopic traffic flow simulation to investigate the amount of time required for a human driver to find a parking space under various levels of parking occupancy and parking pressure. The authors used Reinhold's (1999) definition of parking search to delimit the process and quantify results based on a microscopic simulation. Moreover, the authors extended Reinhold´s analysis by introducing the parking pressure factor [PPF] as the ratio between vacant and demanded parking spaces per hour.

The authors applied this methodology to the case study presented in this paper. The results show that the cruising time for parking at a moderate PPF and a parking occupancy between 75 and 99% is on average two minutes. By increasing the PPF by a factor of 2.5 to 3.5 a positive correlation between an increase of the mean cruising time and parking pressure has been identified. The study recognizes the limitation of the simulation model which is unable to consider illegal parking or seeking alternative parking options outside the study area.

4.2.4 Impact on travel times

In the previous sections we have presented insights into the impacts of vehicle automation on each of the components of the three commuter routes. To provide the link with the following disciplinary perspectives, we recapitulate the results of these estimations in Table 4.2 and Table 4.3.

First, Table 4.2 shows typical travel times for the indicated routes, observed for conventional vehicles and modeled for L4 vehicles. All values are given for traffic conditions characterized by a mean infrastructure saturation of 70% (volume-to-capacity ratio [V_C]: 0.7). The authors assume that L4 vehicles will provide automated valet parking, imposing no additional time costs on the user. Second, based on the estimated travel times, the authors present travel time savings of L4 vehicles compared to conventional vehicles in Table 4.3

Table 4.2: Travel time of conventional and L4 vehicles in the case study

	Route	Travel time for V_C 0.7 [min]	Cruising for parking [min]	Vehicle hand-over [min]	Total travel time [min]
Conven-tional	Freeway	28.0	2.0	-	30.0
	Arterial	29.5	2.0	-	31.5
	Collector	30.0	2.0	-	32.0
Level 4	Freeway	23.5	-	0.5	24.0
	Arterial	27.0	-	0.5	27.5
	Collector	28.0	-	0.5	28.5

Table 4.3: Travel time savings of L4 vehicles in the case study

	Route	Intersec-tions [min]	Links [min]	Cruising for parking [min]	Vehicle hand-over [min]	Total travel time savings [min]
Level 4	Freeway	0.5	4.0	2.0	-0.5	6.0
	Arterial	1.0	1.5	2.0	-0.5	4.0
	Collector	0.5	1.5	2.0	-0.5	3.5

The estimations result in significant travel time savings on all three routes, ranging from 11% (collector road) to 20% (freeway). Therefore, from a daily commuter perspective, the largest travel time saving can be reached on the freeway route, where the main travel time reduction occurs on the freeway segment of the route. Considering the contribution of each infrastructure element to travel time saving, it can be argued that vehicle automation yields the highest impact on travel time on uninterrupted facilities where a further harmonization of already rather homogenous traffic flow brings the desired effect. In contrast, if traffic flow at intersections remains organized in conventional ways (both signalized and unsignalized), in other words without connecting all traffic to a connected intersection agent, intersections will remain the main source of origin-destination delays.

The contribution of the travel time savings by automated valet parking is high for the studied commuter relation but will diminish with increasing trip lengths (and vice versa). Therefore, an examination of the travel time savings yielded by vehicle automation or intelligent transport infrastructure (e.g., high-occupancy vehicle lanes or high-occupancy toll lanes) in relation with the inability to find available parking within the last mile remains a topic for future research.

5 Effects on travel time related user benefits

5.1 Methodology

The estimation of user benefits of automated driving on this exemplary relation focuses on the impacts related to travel time and the benefits arising from the repurposing of travel time ("travel time related user benefits"), as analyzed by Szimba and Hartmann (2020). Other variables affecting user costs, such as decrease in insurance fees due to enhanced safety, decrease in fuel consumption as a result of improved driving efficiency, or additional vehicle costs for full automation (see, e.g., Bösch et al., 2018; Wadud, 2017), are not considered in this analysis. Second-order effects, such as an increase in road traffic due to increased convenience of door-to-door travel by passenger cars, are also not considered in our estimations.

The impacts on travel time related user benefits of AVs are due to increased fluidity of traffic flows and enhanced infrastructure capacity, as demonstrated through traffic simulations in the previous chapter. Furthermore, since an AV does not require a driver to find a parking space, it provides door-to-door transport options. An AV thus allows travel time savings compared to a conventional passenger car.

To monetize time savings, the value of time [VoT] approach used for the evaluation of infrastructure projects in the context of the German Federal Transport Infrastructure Plan 2030 (Axhausen et al., 2014; PTV Planung Transport Verkehr AG et al., 2016) is applied. This results in a value of €6.90 per hour, which represents the VoT of a car commuter for the distance range of 20 to 30 km (Axhausen et al., 2014).

In order to monetize the user benefit generated by enabling the commuter in an AV to conduct activities other than steering the vehicle, further considerations are needed. Kouwenhoven and Jong (2018) explain VoT as the difference between "the opportunity value of time" and "the value of the utility that is created during the travel time," following the VoT concepts by DeSerpa (1971), Evans (1972), McFadden (1981), and Jara-Díaz (2000). Therefore, the possibility to spend travel time on useful or productive tasks increases utility during travel, which in turn decreases the passenger's VoT when using an AV. A lower VoT for users of automated passenger cars is confirmed by various authors such as van den Berg and Verhoef (2016), Wadud et al. (2016), and Stephens et al. (2016).

Based on average willingness-to-pay values for using additional services in an automated car identified by Fraunhofer-IAO and Horváth & Partners (2016), Szimba and Hartmann (2020) derive a user benefit of €17.55 per month for commuting trips whose duration is up to 30 minutes. If the duration of the fully automated part of the commuting trip is less than 30 minutes, this amount is reduced according to the assumption that the derived benefit value increases linearly in the travel time interval [0, 30 minutes].

5.2 Results

The results of the estimation of user benefits per return trip are summarized in Table 5.1 (user benefits due to time savings), Table 5.2(user benefits due to repurposing of travel time), and Table 5.3(total user benefits).

User benefits that accrue from time savings and the commuter's ability to use travel time for activities other than driving the car are estimated at €219–374 per year, depending on the route chosen. Extrapolating these values over a depreciation period of six years results in benefits of €1,314–2,244 over the economic lifetime of a passenger car (without discounting), which represents a considerable asset.

Table 5.1: User benefits of travel time savings (source: Szimba & Hartmann, 2020).

	Route	Travel time savings [min/day]	User benefits [€/day]	User benefits [€/year]
Level 4	Freeway	12	1.38	304
	Arterial	8	0.92	202
	Collector	7	0.81	177

Table 5.2: User benefits of repurposing of travel time (source: Szimba & Hartmann, 2020).

	Route	Driving time in automated mode [min/trip]	User benefits [€/day]	User benefits [€/year]
Level 4	Freeway	10	0.32	70
	Arterial	7	0.22	49
	Collector	6	0.19	42

Table 5.3: Total user benefits (source: Szimba & Hartmann, 2020).

	Route	Total user benefits [€/day]	Total user benefits [€/year]
Level 4	Freeway	1.70	374
	Arterial	1.14	252
	Collector	1.00	219

Compared to the benefits due to travel time savings, the benefits of repurposing of travel time are limited, albeit not negligible. The highest total benefits are expected for the “freeway” route, since this route option allows higher time savings than the other routes and enables automated driving over a comparatively long period of time. The lowest benefits are estimated for the “collector” route option featuring a relatively low level of travel time savings and a comparatively short period of time in which automated driving is possible.

6 Impact on urban development

The range of effects of automated driving on urban space, its design and use, but also on the mobility network and the spatial development of entire (metropolitan) regions is not yet fully forseeable. In any case, though, the emerging planning challenges are complex (cf. Heinrichs, 2015, p. 236). They include the reorganization of parking as well as the possible revaluation of residential areas, shopping destinations, or work places.

The use of AVs in the city as a supplement to local public transport could make a significant contribution to reducing traffic volumes in cities, influencing transport demand, and changing the need for parking space. AVs are expected to make more efficient use of available road space and make traffic safer. Optimized driving will allow narrower lane widths and fewer lanes, which, along with the elimination of parking, will free up land that can be converted to other transportation uses such as bicycle lanes or wider sidewalks, or turned into green areas. With technological developments, both organizational and urban planning questions and tasks arise: with regard to the redesign of traffic areas, to the conversion and design of parking areas that are no longer needed, with regard to the placement of collective parking facilities elsewhere, and much more. In this context, not only considerations arising from the requirements of changed traffic flows are important, but also those resulting from the existing urban context; not everything that is technologically feasible is desirable from an urban planning or urban society perspective.

6.1 Perspectives for spatial transformation of streetscapes

In the following section, we look at some benefits for urban spaces, focusing on a defined district with priority-to-the-right streets. These types of intersections can be found in many European Wilhelminian style districts from the second half of the 19th century with an urban fabric consisting mostly of closed blocks, often with public uses on the ground floor and additional uses in the yards.

In these districts, focus areas can be precisely defined. For our study, we chose a part of Karlsruhe's Oststadt district that can be regarded as representative for many other Wilhelminian style districts in Germany and Europe. The area under investigation covers approximately 45 hectares, is well connected, and provides a wide range of inner city functions besides housing. We assume that within this area, the L4 vehicles are allowed to travel fully independent, at low speeds with and without passengers from the origin location – home, store, workplace, etc. – to a central parking facility located in the district, and pick up the user again if needed. Furthermore, we assume that the introduction of

AVs will make all areas that are currently reserved for on-street parking available for other uses (e.g. McDonald & Rodier, 2015).

The L4 scenario outlined above provides a wide range of opportunities for repurposing and transformation. The freed-up public space could be transformed for different uses and new designs, e.g., for other traffic purposes, for additional commercial and residential uses, or for more green and public spaces (Heinrichs, 2015). We evaluate the introduction of new functions into the district and analyze the spatial potential of the freed-up spaces. We address the following key questions: Can car-oriented urban space be retrofitted for other uses? Is there any potential for construction on the freed-up spaces? What options could arise for a new zoning of street and traffic spaces, meeting and recreational spaces?

Figure 6.1: Overview of the different types of parking spaces in the area under investigation.

6.2 District and classification of streets and parking zones

The inner circulation of the analyzed district Oststadt is organized by local access roads with priority-to-the-right intersections. These are mainly two-lane streets with one lane for each direction. In the district itself, no designated bicycle lanes exist. The width of the sidewalks ranges from 1 m to 2.5 m. Buildings on the street side are generally accessed from the street, buildings within block areas via numerous openings for delivery traffic as well as customers and residents. Parking is permitted on all streets. In total, nearly 1,820 parking places covering roughly 2 hectares of land are located in the public space.

To examine the transformative potential of the area, street widths and types of parking space were mapped and analyzed in a cross-sectional fashion (Figure 6.1). In the Oststadt district, they can be classified into five types according to the arrangement of the parking places in relation to the lanes: Parking on one side, parallel parking, parallel and perpendicular/angle parking, perpendicular/angle parking, additional parking along a median. Depending on the parking type, the gained space varies from 2 m^2/m to up to 10 m^2/m. Thus, also the proportion of the potential areas varies.

6.3 Examples for spatial transformations of the street space

The conversion of parking places could make an overall area of more than two hectares available for repurposing. Unsealing these areas and planting trees could contribute to improving the microclimate in the district and could thereby help to meet the climate protection goals set out in Karlsruhe's spatial model. The positive effects of increased vegetation in the district could balance temperature differences. Planting additional trees along the streets could create a continuous green street network that lends the district a new, green character. In Klimakvarter, the first "climate-resilient" quarter in Copenhagen, various measures were implemented, both in the public space and in the courtyards (Klimakvarter, 2018). Surfaces have been unsealed, vegetation planted and innovative water storage introduced. Such measures do not only improve the microclimate and equip the city for heavy rainfall, but also increase biodiversity through the emerging green links and are well suited for a transformation of the Oststadt district (Figure 6.2).

The newly gained areas could also be used to implement the concept of urban farming, which promotes vegetable gardens in the city, while adjacent sidewalks could be used for functional densification of street spaces. Self-proclaimed "Edible Cities" such as Todmorden (UK) and Andernach (Germany) have already experimented with different types of raised bed gardens in public spaces that are accessible to everyone (Kosack, 2016). In these cities, many of the public green spaces offer planted food for sharing that can also contribute to social sustainability.

Figure 6.2: Essenweinstraße: current situation and scenario with denser vegetation and open waterways. (© Michael Wicke)

Figure 6.3: Ludwig-Wilhelm-Straße: current situation and scenario “stronger mixture of functions“, depicted from a top view. (© Michael Wicke)

So-called micro projects – as promoted in San Francisco’s parklet program to “reimagine the potential of city streets” – give good insight into the countless possibilities for repurposing former parking lots (Davidson, 2013). Since 2010, parking places in San Francisco have been converted into temporary seating areas, playgrounds, bicycle parking spaces, and flower beds. Today, they provide spaces that can be used for social interactions such as debating, relaxing, watching everyday life, or for sports activities and playful interaction and can thus boost shops or restaurants with additional areas.

Figure 6.3 shows the restructuring potential of Ludwig-Wilhelm-Straße. The offset arrangement of parklet-like interventions enlivens the street space and divides it into smaller sections. In the gastronomy area, one zone is equipped with temporary furniture. In combination with the trees, this represents a considerable increase in quality for café visitors during the summer months and nearly doubles the restaurant's "sales area".

Finally, structural densification is also a possibility in selected areas. Workshops and mobility stations, district libraries or even residential buildings specifically designed for residual areas and temporary uses could be implemented as experimental projects. "The Unreal-Estate House", a crowdfunded wooden house developed by architect und activist Van Bo Le-Mentzel that can be built by anyone, could serve as a model for such minimalist housing types (Le-Mentzel, 2013). Other projects demonstrate the potential of minimalist housing through transformed caravans, providing self-sufficient systems that can purify their own water and hence require less infrastructure to connect to (Reek, 2016).

The different situations analyzed show both the potential and the constraints that arise for the various kinds of transformation. The container-sized living units are exposed to a large public and completely redefine the pedestrian space. At the same time, the quality also becomes evident considering the immediate vicinity to newly planted greens. Since the areas under discussion are former parking places, they are generally located between two traffic areas, with the street on one side and the sidewalk on the other, thus offering limited privacy.

Nonetheless, times of increasing housing shortage require alternative housing concepts, e.g., living in small spaces, as well as temporary housing and housing for certain groups of people such as students, migrants, or pensioners could be reconsidered. However, applicable construction laws on use, density, and spacing further restrict the options for development. Only street types with multiple parking lanes, e.g., including parking in the center of the street, could be used for housing solutions on or along the parking places along the median.

6.4 Benefits for the Oststadt district

Although a lot of usable space would be gained by banning on-street parking, it is evident that due to the location and dimensions of these spaces – i.e., their small-scale structure and fragmentation – the areas are only suitable for certain uses and require special examination. Larger construction projects seem to be complicated and costly. At the same time, the gain for the public space would be considerable. Small-scale, possibly also temporary, structural interventions could balance out existing usage deficits. Legal matters would also have to be examined; e.g., whether the space without an allocated function would have to or should not be assigned in terms of property law. When setting up gardens, would they be temporally transferred with a lease agreement? Who would be responsible for maintaining the gained public space? Would privatization of the areas be desired to ensure maintenance or would this have the opposite effect and endanger the common good? In any case, it would be necessary to incorporate the measures into a larger overall concept. How much density can the district cope with? What is desired and sensible: more greens or more functional features? And even in case of a sole redistribution between the road users – cars, cyclists, and pedestrians –, the distribution of benefits would have to be negotiated.

We discussed an almost ideal L4 case with regard to the resulting spatial potential. Yet, many directly related questions with potential impacts on the urban space have not been considered. Some parking places may retain their function despite automated driving, loading zones for commercial units or parking zones for deliveries and customers, for example, have not been qualified or quantified. Could short-term parking zones potentially be required for AVs? Should this be particularly considered for people with restricted mobility? How can district garages for AVs be spatially and functionally integrated in such a way that they do not become merely faceless parking garages (like the warehouses we currently see in cities), but instead add spatial quality and perhaps also make a functional contribution to the district by mixing uses?

The economic consequences are hard to predict. Would the altered streets raise the quality of life, which would be reflected in higher rents and thus lead to gentrification, or would the changed diversity and increased number of temporary users lead to a different development? Would the streets be constantly congested with empty AVs circling between rides or will a new sharing economy lead to an entirely changed modal split? The ramification of AVs will be highly determined by regulations. If, besides travel time gains and lean back times, the urban layout will be addressed, potential spatial alterations can be discussed. To ensure an impact that adequately addresses current urban challenges, it is crucial to consider these spatial implications instead of letting a technical revolution shape the image of our cities.

7 Discussion

The overall objective of this paper was to take a common L4 vehicle automation case and compile a number of interdisciplinary perspectives on that case, or, more specifically, travel time related user benefits for commuters and potentials for improving the sustainability and "livability" of an urban district.

With regard to travel time savings, the highest savings can be achieved by commuting via the freeway route with a travel time reduction by six minutes. This is in the range of 25–30% of travel time reduction compared to a system using conventional cars. For the route via the collector road, travel time savings amount to 3.5 minutes. In the latter case, more than half of the time savings are due to automated parking at the Oststadt destination. The monetization of users benefits for commuters results in a maximum of €374 per year. This value represents a significant amount – especially given that the benefit value only considers commuting trips. Nevertheless, there are still some uncertainties when it comes to assessing the benefits generated by the repurposing of travel time. On the one hand, users might learn how to use this newly gained "free" time in the car as efficiently as possible – and thus further increase its benefit. On the other hand, habituation effects might occur that could negatively affect the individual perception of the gained benefit.

Looking at the potentials for urban planning, the analysis points to a broad range of possibilities for using the public space that will be freed up after the introduction of centralized parking. Of course there is a huge transformative potential: In the Oststadt, parking spaces in particular could be transformed to make the district a little greener. Trees could be planted; other options could include urban farming or the improvement of outdoor spaces to make visits to cafés more attractive. Further alternatives are related to a structural densification (workshops, mobility stations, residential areas, alternative living concepts on smaller lots). However, the limitations of the different aspects of transformative potential become clear as well: for example, new spaces on former parking areas are small, scattered throughout the district, and situated between two roadways and sidewalks, leaving limited room for privacy.

Our results reveal that in all the investigated dimensions at least moderate benefits can be expected. In our specific case in Karlsruhe, aimed at representing a typical commuting relation to a dense urban district, L4 cars could have a significant influence on traffic flows and capacities (mostly outside the city, where roads are within the assumed ODD), value of time, and, to a lesser extent, also on urban design. It is important to note that the benefits are not restricted to mobility itself but include the possibility to improve the quality of life in urban areas. More and more people are expected to live in cities, and Karlsruhe has also been growing over the last years. However, the limits and constraints of the potentials outlined above (particularly the size and distribution of the freed-up parking spaces) require a close interlinking, e.g., with regulatory approaches to ensure that the potentials can actually be realized.

7.1 Limitations and potential areas of conflict

The analysis presented above has a number of important limitations. Most importantly, our case study could not consider how the introduction of L4 vehicles and the resulting changes in people's routines might generate feedback effects on the framework conditions of the case itself. Such effects could, e.g., support undesired urban sprawl into Karlsruhe's suburban and rural surroundings or modal shift away from more environmentally friendly modes of transport. Both could be induced by the higher attractiveness of (automated) L4 car commuting, at the same time risking some of the desired benefits through higher traffic volumes and more congestion instead of improved traffic flow. The consideration of such feedback effects at the same time points to potential areas of conflict in the widening scientific and societal debate about automated driving.

First, our quantitative results underpin the likeliness of an increased attractiveness of commuting by car. Even when considering higher purchasing costs of AVs, as shown by Szimba and Hartmann (2020), the generalized user costs of individual motorized mobility in AVs are expected to decrease, since commuters would, e.g., have the opportunity to start their work as soon as they leave their home. The specific case analyzed above, however, does not consider second-order effects such as increasing road transport demand (modal shift from public transport or active modes to car transport), allowing new user groups easier access to car transport, or changes in land-use patterns (see, e.g., Fagnant & Kockelman, 2015; Harper et al., 2016; Sivak & Schoettle, 2015; Szimba & Orschiedt, 2017). Modal shift and induced demand may also outweigh some of the estimated benefits due to time savings by an increase in congestion etc. Nevertheless, the availability of AVs and thus more attractive car commuting could make suburban areas more appealing to many people which could increase suburbanization. Such urban sprawl, including the associated follow-up costs (e.g., for the development of new settlement areas on the outskirts), would clearly counteract the widespread political goal of extending existing settlements in a resource-efficient manner.

Second, the introduction of AVs could lead to a wide range of spatial transformations within the existing urban fabric, depending on potential L4 ODDs, which may not only offer advantages. While purposefully excluded in our case, extending L4 further to inner city collectors could require a more or less strict separation of the road users in order to unleash the full (technological) potential of the AVs in an urban environment. Combined with a potential increase in the number of vehicles on the streets (due to improved and dense (car) traffic flow), this would bring undesired side effects for other road users. It would limit the permeability of urban space for people and raise the question of how the mix of different traffic modes should be organized (e.g., with dedicated zones for the safe transition from automated to manual driving) and balanced in the future, including the risk of undesired modal shift to car traffic because of its increasing relative attractiveness (see above).

These are only some of the many possible spatial impacts that could result from the introduction of AVs and are not desirable from a spatial and urban planning perspective. Yet, focusing on a more technologically oriented perspective, others may support a more selective development in favor of AVs. Therefore, keeping the potential areas of conflict and tradeoffs in mind is crucial for informed and balanced decision making around AVs. This is also relevant since the way society deals with L4 could also form the basis for how L5 automation can evolve if the technological development follows an evolutionary pathway.

8 Outlook

The results presented in the previous sections show that L4 vehicle automation already has the potential to improve the situation for commuters and residents. However, it also becomes obvious that these potentials have limitations. This is an important finding since some experts expect the commercialization of L4 vehicles rather soon, whereas the introduction of L5 vehicles is expected much later. It can be assumed that field trials at L4 will be further extended in the near future. Many effects that are usually discussed for L5 situations may already become effective at L4 stage, at least to a certain extent. That said, we must emphasize the crucial importance of a (case-specific) definition of the ODD of the L4 vehicles to be analyzed. The category as such, as defined by SAE International (2018), is not sufficient for a detailed analysis of the potential benefits and the transformative potential of L4 vehicles. The actual effects crucially depend on the various potential ODDs of such vehicles (and the use cases they enable), which in turn define how actual trips are affected and how the resulting benefits and opportunities will in fact unfold.

Looking at the built environment, urbanization is an ongoing process that will require even more options for urban redesign in the future. Bringing together the interdisciplinary perspectives from our case shows how critical integrated approaches are, including strict measures and restrictions regarding traffic and parking in urban districts, for actually achieving the potential benefits of automation and increasing livability. A variety of studies discusses the potential of pro-active AV implementation strategies by cities for urban mobility. For example, setting up field tests could be worthwhile for investigating the practicability of redesigning urban spaces on site and in real time on a trial basis (Rupprecht et al., 2018). The requirements, constraints, difficulties, and challenges of interventions and their potential reciprocal effects could be displayed in such field tests. Without an integrated perspective, however, negative effects of increasing traffic and more parking could easily prevail, fostered by automation.

Therefore, a broad range of further research questions needs to be tackled before we get the full picture of the impacts and benefits of vehicle automation. Additional research is required to estimate the magnitude of the impact of automated driving on travel behavior and, particularly, to better understand the interrelation between road automation and land-use patterns. More attractive commuting trips enabled by automated cars, combined with excessive land prices and housing costs in metropolitan areas, are likely to increase the attractiveness of places of residence that are located further away from the workplace. A better understanding of these interrelations will be an important basis for the development of urban and spatial policies to prevent further urban sprawl and second-order induced traffic. Moreover, the new options for urban space at district level obviously cannot be fully covered by the established legal practices and institutionalized routines of urban planning and traffic management. A number of legal questions (who should own/use the freed spaces) or urban design issues (how to integrate central garages for AVs into the urban landscape) should thus be addressed. Stakeholder dialogues and field trials could induce learning processes in future projects.

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