7. Towards the machine-readable city?

Autonomous driving and HD mapping as latent conflicts in urban future-making

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Introduction

In August 2023, Waymo – a subsidiary of Google's parent company, Alphabet – introduced a fleet of fully self-driving cars in the city of San Francisco.[1] As with well-known ride-hailing services such as Uber, Waymo's shuttles can be booked via a smartphone app. Passengers are picked up, however, not by a human driver but by a fully automated car-robot: its driver's seat eerily empty, its steering wheel moving by itself (Waymo, 2024). While Waymo's autonomous vehicles (AVs) have stirred much global media attention since their introduction (Mickle et. al., 2023), as of yet, there is considerably less awareness about one of the most crucial operations that centrally underlies virtually any effort towards large-scale AV implementation: so-called HD mapping (Mattern, 2017; Alvarez León, 2019a). Many times more accurate and variously more detailed than previous GPS-based mapping procedures such as Google Street View, HD maps provide fully three-dimensional digital replicas of entire cityscapes and, as such, serve as an indispensable digital compass for self-driving cars in the ever-changing and chaotic environment of the urban streetscape.

Critical scholars in and beyond urban geography have not remained oblivious to the growing presence of AVs in urban areas (Stilgoe, 2018; Jones et al., 2021). Next to explorations of AV use cases beyond the self-driving car – such as drones (Jackman, 2023), delivery robots (Macrorie et al., 2021), or modular

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freight vehicles (Hopkins, 2023) – it has been practises of AV testing and trialling that have attracted a great deal of critical scholarly attention lately (Talebian and Mishra, 2018; Marres, 2020). While these literatures have shed much-needed light on the advancing urban rollout of AVs, including its associated implementation problems such as hyperbolic promises by corporate developers and a lack of acceptance by users (Stilgoe and O'Donovan, 2023), there exists a methodological tendency in many of these studies to treat AVs as 'closed' technical end products or *things*. Vice versa, the underlying technical, social, and political *processes* that make possible the 'discrete unit' of the AV capsule in the first place remain far more unexplored. Likewise, the procedure of HD mapping has only gradually come under more explicit scholarly scrutiny (for a pioneering early exploration, see Mattern, 2017). This is despite the fact that, as noted by Luis Alvarez León, the use of 'artificial intelligence–enabled HD and 3D maps is reconfiguring the mobile spatial media environment within (and around) cars, while simultaneously laying the foundations for an entirely new way for cars to navigate – and ultimately produce – space' (2019b: 364; similarly, Alvarez León, 2019a). HD maps, in short, have the potential to substantially augment the urban built environment by enhancing it with new machine-readable layers of geographic data produced not for the human sensory apparatus but for the affordances of the self-driving car's multi-perspectival 'machine eye' (Dodge and Kitchin, 2005; Kitchin, 2014; Rabari and Storper, 2015).[2]

Situated at the interface of the city as an existing physical structure of second nature and as a rapidly expanding digital reality of third nature (Wark, 1994), large-scale HD mapping marks a primary site of urban future-making. Built environment professionals in and beyond state institutions – urban planners, public officials, political decision-makers, policy 'experts', regulators, advocacy groups, media commentators, NGOs, activists, and more – find themselves confronted with a novel urban practice and technology that brings with it profound urban conflicts. At the level of professional space-making, as I argue in this chapter, HD mapping procedures are accompanied *by* and deeply embedded *in* three broader conflict constellations of today's entrepreneurially-

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[2] On the idea of the 'machine eye', see Harun Farocki's extensive filmic work (Paglen, 2014).

oriented 'tech urbanism': (1) conflicts of urban governance, (2) conflicts of urban regulation, and (3) conflicts of urban imagination.[3]

In pursuing these conflict constellations, two important qualifications are needed. First, inspired by the idea of urban intelligences beyond the big-tech corporation and its stiflingly narrow vision of urban 'smartness' (Mattern, 2021), I proceed from the hypothesis that HD mapping does not so much instantaneously 'disrupt' the urban fabric in a tabula-rasa-like instant of Promethean re-creation (critically, Namberger, 2024). Rather, what is at stake and in need of careful disentanglement is a full bundle of inherently conflictual processes, procedures, and operations along which HD mapping has started to be woven into the existing urban fabric. Second, I understand AV development in general and HD mapping in particular as forming part of what Aaron Shapiro (2021) has called 'the urban stack': hierarchically layered assemblages of analogue and digital urban infrastructures, hardware, and software, allowing for the sensing, processing, and mass application of large-scale urban data in the context of corporate value extraction. Given the largely black-boxed quality of the urban stack (Shapiro, 2021: 28), it may not be too surprising that – as I discuss below – HD mapping's conflicts of governance, regulation, and imagination figure not so much as 'open', clearly visible confrontations between opposing groups or stakeholders, but rather as *latent* conflicts of urban future-making: conflicts that, anchored deeply within the digital code and opaque operations of the urban stack, have not yet fully surfaced at the level of broader societal awareness. In this sense, the generation of HD maps shares much with the closely related and equally non-transparent procedures of training data generation in the context of autonomous driving (Schmidt, 2022).

Starting from these two assumptions, in what follows I take a closer look at some of the ways in which HD mapping has started to intervene in certain urban areas and particular political arenas of existing urban space. By doing so, I will pursue two general aims. First, in the next section, I discuss current AV testing and implementation as, in essence, large-scale exercises in trying to mitigate and make manageable the sheer unpredictability of the urban

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[3] On the topic of tech urbanism, see Mattern (2021), and Cugurullo et al. (2023). On conflicts of governance in relation to current tech urbanism, see Wiig (2015). On conflicts of regulation vis-à-vis current tech urbanism, see Stark et al. (2021). On conflicts of imagination in relation to current tech urbanism, see Sadowski and Bendor (2019).

streetscape. Second, HD mapping can be understood, as discussed in the subsequent section, as one of the most technologically advanced instruments of urban risk mitigation in the context of comparatively open scenarios of AV implementation. Third, using the Testfeld Autonomes Fahren Baden-Württemberg (TAF BW), a project of HD mapping and AV implementation in southwest Germany as an empirical vignette, I illuminate the broader yet largely latent conflicts of governance, regulation, and imagination that have accompanied the realization of this local venture in particular and of autonomous driving and HD mapping in general. Building on these insights, a conclusion summarizes my findings and makes some methodological suggestions for further research on autonomous driving, HD mapping, and similar developments of high-end tech urbanism.

Mitigating uncertainty: Autonomous driving between closed and open urban scenarios

As scholars of various stripes and times have pointed out in relation to recurring waves of socio-economic crises and their urban reverberations, uncertainty, volatility, and unpredictability have long been vital ingredients of urban life under capitalism (Mumford, 1938; Simmel, 1969). In a similar vein, Zeiderman et al. have recently noted that, in (partly simplistic) juxtaposition to rural environments, the city has often been found to be ‘a fundamentally unknowable and unpredictable environment’ (2015: 282). In reaction, uncertainty has often been made the ‘target of urban intervention’, which has included recurring and oftentimes futile ‘attempts to mitigate and manage it’ (ibid.).

In this section, I suggest it is the sheer messiness and fundamental unknowability of what Henri Lefebvre (2003) once called the ‘urban phenomenon’ that today’s practices of AV testing and selective real-world implementation have in many ways run up against. Consider, for instance, the following characterization of the encounter between AVs and the urban environment provided by Dawn E. Holmes: an AV’s sensors, as Holmes writes,

> have to be programmed to detect shapes and distinguish between, for example, a child running into the road and a newspaper blowing across it; or to detect, say, an emergency traffic layout following an accident. However, these cars do not yet have the ability to react appropriately to all the problems posed by an ever-changing environment. (2017: 11)

What the AV challenge is about, in many respects, is the technological and regulatory management of urban uncertainty: the AI-powered mitigation of the sheer infinite variability of the urban streetscape with its myriad of erratically moving shapes and forms, subjects and objects.

Among current practices of AV testing, trialling, and implementation, different approaches towards mitigating urban uncertainty can be identified (Cugurullo et al., 2021; Stilgoe and O'Donovan, 2023). Testbed trials, for instance, minimize uncertainty by inserting AV testing into largely closed-off, fully controllable special facilities such as repurposed racetracks and other custom-built sites (Dowling et al., 2023: 28–30). Examples include the DEKRA open-air test facilities at Lausitzring in Germany (Seyfert, 2023), purpose-built AV test facilities by established car manufacturers, such as Volvo's AstaZero Proving Ground Centre located near Gothenburg (Volvo Cars, 2014), or joint ventures between governments, universities, and the tech and automotive industries, as in the University of Michigan's 'Mcity' (Dowling et al., 2023: 29). Addressing the unpredictability of the city by largely fencing it off, testbeds, as Dowling et al. write, 'are deliberately isolated from the messy materialities, socialities and institutional landscape of the city. They instead simulate urban conditions, creating, where possible, a controlled environment or "in vitro" experiment' (2023: 28). Partly reminiscent of what Keller Easterling (2005: 99) has called the 'automated enclaves' of container ports and logistics warehouses, AV testbeds arguably mark an extreme case within current modalities of AV testing. Usually taking place in highly controlled and widely human-devoid purpose-built facilities, the tests exclude urban uncertainty almost by definition. This may create close-to-perfect testing conditions, yet it does not resolve the remaining challenge of hard-to-predict urban environments.

Partly more open than AV testbeds, so-called precinct trials display further interesting dynamics of avoiding urban uncertainty (Stilgoe and O'Donovan, 2023). Precinct trials often take place within closely delimited geographical areas, many of which are inaccessible to broader automotive traffic and urban street life. What one typically finds here, in short, are trials with 'electric autonomous shuttle buses on short, low-speed fixed routes, usually contained within a business park, university campus or innovation precinct' (Dowling et al., 2023: 30). One paradigmatic example is Berlin's Charité hospital precinct where, since 2018, two autonomous mini busses have roamed the campus facilities at a speed of 20 kilometres per hour over a total area of 270,000 square metres (Charité, 2017; TNW, 2022). While ambulances, private cars, pedestrians, and cyclists are allowed into the campus, dynamics of spatial seclusion are again at work, as the precinct's park-like character hardly compares to the much more complex, often outright chaotic, nature of the Berlin streets surrounding the hospital.

Beyond closed-off testbeds and securitized precinct trials, pilot programmes with digitally augmented freeway lanes provide another insightful perspective on the reduction of urban uncertainty. In the US state of Michigan, Cavnue – a subsidiary, once more, of Google's parent company, Alphabet – has partnered with the Michigan Department of Transportation to repurpose one of Interstate 94's freeway lanes as a dedicated test lane for connected and automated vehicles. At the heart of the programme, which started in August 2020, is the digital augmentation of parts of Michigan's existing freeway infrastructure, enabling both vehicle-to-vehicle (V2V) as well as vehicle-to-infrastructure (V2I) communication (Cavnue, 2020). Similar to established infrastructural policies such as dedicated HOV lanes,[4] Cavnue's Michigan pilot in many ways points towards the continued splintering and pay-per-use unbundling of existing transport infrastructure under neoliberal urban governance (Graham, 2000). Most interestingly, the programme foreshadows a feasible approach towards AV implementation in the context of interurban freeway systems, which – by way of their very design and *built-in* isolation from broader urban life – provide a far more AV-friendly environment than, by possibly greatest contrast, inner-city streets.

From these highway trials it is a comparatively small step to the arguably most complex use case of current AV implementation: the insertion of AVs – as in the example of Waymo in San Francisco – into widely more open urban scenarios. In the case of such full urban implementations, as I discuss in the next section, AVs must leave behind the preordained paths of precinct trials or the linear simplicity of digitally augmented freeway lanes; instead, what they face is the sheer unpredictability and contingency of the dense, inner-city streetscape. In this most challenging urban environment, AVs must rely on a new instrument of spatial control and prediction: the HD map.

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[4] HOV stands for high-occupancy vehicle. Mostly in North American contexts, HOV lanes have been used by transport agencies as a congestion reduction strategy by reserving certain highway lanes for vehicles with at least one driver and one passenger inside.

HD mapping and the quest for 'real-time' built environments

As noted above, one of the most central processes underlying today's efforts at large-scale urban AV implementation is the procedure of so-called HD mapping (Mattern, 2017; Alvarez León, 2019a). Variously more elaborate than Google Street View (Anguelov et al., 2010), HD maps provide AVs with a hugely detailed three-dimensional model of a city's built environment, including centimetre-precise data on building contours, street curvature, road signs, and more (Wang et al., 2017). Once outside the more confined and manageable spaces of testbeds, precincts, and highway lanes, the basic way AVs orient themselves is by constantly cross-referencing real-time sensory inputs with pre-created HD maps (Waymo, 2021: 8). These maps, as Alvarez León notes, 'are created through sophisticated, and often proprietary, combinations of sensing and mapping technologies, which feature continuous, multimodal, and extensive data collection and processing' (2019a: 10). Compiled from a myriad of data inputs and multi-perspectival scans of a city's built environment, HD maps serve as the ultimate socio-technological instrument for Waymo and other corporate and non-corporate AV developers to mitigate, reduce, and manage – as precisely as technologically possible – urban uncertainty. Thus, in what follows, I will explore the process of HD mapping in more detail, foregrounding how it interweaves varied practices of urban data collection, annotation, and processing in order to augment the urban built environment with a new digital, fully machine-readable layer of geo-referenced data allowing AVs to 'read' the urban built environment in unprecedented granularity (Dodge and Kitchin, 2005; Rabari and Storper, 2015).

HD maps are generated from a vast array of input data (Mattern, 2017). First of all, tech companies such as Waymo, GM's Cruise, or HERE Technologies[5] send their AV prototypes out into the streets for scanning and recording entire cityscapes (Wang et al., 2017; Waymo, 2021: 18). Equipped with video cameras, radar, inertial measurement units, ultrasonic sensors, GPS, and LIDAR lasers, these vehicles are able to capture the city at an unprecedented level of detail. While constant triangulation between all of these sensory inputs is key to AV navigation, LIDAR – short for 'light detection and ranging' – has a special role to play with regard to the creation of three-dimensional HD maps.

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[5] HERE Technologies is a location data provider specialising in HD mapping for autonomous navigation. It is majority-owned by a conglomerate of the German car makers Audi, BMW, and Mercedes-Benz (Alvarez León, 2019a: 371).

As in the words of Waymo, LIDAR 'works day and night by beaming out millions of laser pulses per second – in 360° degrees – and measuring how long it takes to reflect off a surface and return to the vehicle' (2021: 14). On the basis of these measurements, it is possible to reconstruct a fully three-dimensional model of both the mediate and immediate surroundings of an AV, including street lanes, buildings, traffic lights, and more. LIDAR scans, in short, provide the very basis for any HD map.

These street-level LIDAR scans are further enhanced with a multiplicity of geo-referenced data stemming from satellite and drone images, public and private mapping databases, crowdsourcing projects, and more (Mattern, 2017). The image below (Figure 1), for instance, is taken from a scientific publication, fittingly entitled 'TorontoCity: Seeing the World with a Million Eyes', of Uber's (now abandoned) AV development programme conducted by computer scientists at the University of Toronto (Wang et al., 2017).[6] More than anything else, it provides an exemplary insight into both the variety and the richness of data used for the compilation of AV-ready large-scale HD maps. As such, the ambition of Uber's project was to capture and remodel the entirety of the Toronto city region's built environment in three-dimensional virtual space – numerically speaking: '712.5 km^2 of land, 8439 km of road and around 400,000 buildings' (Wang et al., 2017: 3009). To this purpose, Uber's research team, in their own words,

> gathered a wide range of views of the city: from the overhead perspective, we have aerial images captured during four different years as well as LIDAR from airborne. From the ground, we have HD panoramas as well as imagery and LIDAR data captured from a moving vehicle driving around in the city. We are also augmenting the dataset with imagery captured from drones. (Wang et al., 2017: 3009)

These and other combined data sources allowed Uber to extract streetscape information as detailed as, for instance, the positions, species, and trunk radiuses of trees (Wang et al., 2017: 3013). Conceived as a new benchmark

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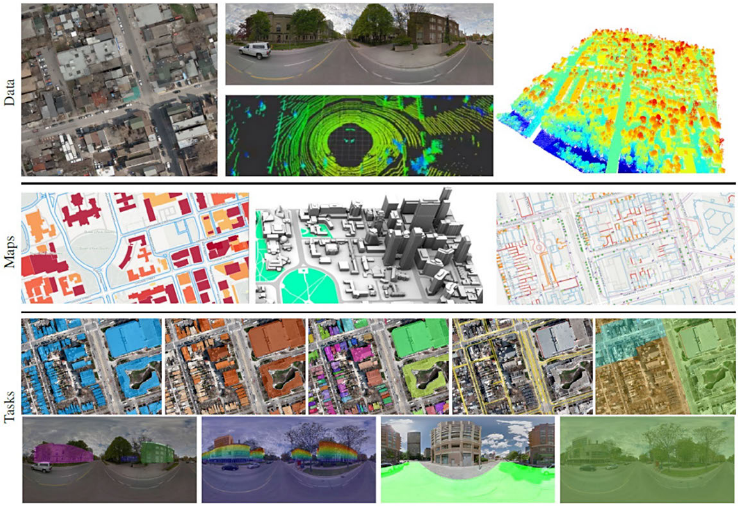
[6] This cooperation between the US company and researchers at University of Toronto came into existence when Uber poached AV machine vision expert Raquel Urtasun, a professor for machine vision at the University of Toronto's computer science department (Silcoff, 2017). In the following years, Urtasun and her team's research directly fed into the AV development programme of Uber's research and development arm, the Uber Advanced Technologies Group (Uber ATG).

for a global research community engaged in AV-driven machine vision, the TorontoCity data project illustrates both the imperatives and the ambitions that come with large-scale HD mapping.

Figure 1: Graphic depiction of various data sources used by Uber ATG to create the TorontoCity benchmark: a fully three-dimensional remapping of the entire Greater Toronto Area.



Source: Wang et al. (2017: 3010). Image reproduced here with the kind permission of Shenlong Wang.

As with the testbed, precinct, and freeway trials above, HD mapping is inextricably linked to the task of reducing urban uncertainty. In case of the HD map, there is both a spatial and a temporal dimension to this task. Spatially, HD maps aim at the re-creation of the urban built environment at a maximum of geographic detail. However, there is also a decisive element of territorial limitation at work. It is largely due to the extreme level of detail needed, and the ensuing high costs, that HD mapping has been projected onto the urban ground in a highly selective and uneven fashion. The industry term for this phenomenon is that of the 'operational design domain' (ODD). An ODD defines not only the strictly geo-fenced outer limits of an AV's area of operation but also the weather conditions and times of day during which an AV may safely be used. As Waymo explains, its AV system is 'designed so each vehicle does not operate outside of its approved operational design domain. For example, passengers cannot select a destination outside of our approved geography, and our software will not create a route that travels outside of a geo-fenced area, which has been mapped in detail' (2021: 16). Spatially, the challenge of HD mapping is, in sum, one of maximizing geographic detail *within* an ODD while gradually expanding any existing ODD.

In temporal terms, on the other hand, HD maps require the unending task of updating and repeatedly realigning existing map data with a virtually infinite number of changes in the real world. Such changes can be caused, for instance, by temporary building sites, emergency barriers, traffic jams, accidents, lane changes, and more. Again, there is an interesting industry term signifying the central aim of temporal synchronicity between the *real* and the *virtual* worlds: 'time to reflect reality'. Time to reflect reality, as Shannon Mattern notes, marks 'the metric of lag time between the world as *it is* and the world as it is known to machines' (2017: n.p.). Reducing this parameter to an absolute minimum is, in short, one of the central challenges of HD mapping and, at the same time, points towards one of its ultimate ambitions-cum-ideologies: the 'real-time' city (Kitchin, 2014).

Latent conflicts of urban future-making: Autonomous driving and HD mapping between governance, regulation, and imagination

Building on the above insights, in what follows I take a closer look at some of the primary conflicts and contestations at the heart of HD mapping's advancing urban implementation. As I argue with a particular view to the level of professional space-making, urban AV implementation in general and HD mapping in particular incite and are embedded within three broader yet largely *latent* conflicts of urban future-making: (1) latent conflicts of governance, (2) latent conflicts of regulation, and (3) latent conflicts of imagination. By discussing these three fields of conflict in the context of the Testfeld Autonomes Fahren Baden-Württemberg below, the following sections will widen the scope of my above explorations from HD mapping 'as such' to autonomous driving in a more general sense. This has to do with the fact that, in empirical reality, the phenomena of HD mapping and autonomous driving exist in almost inextricable mutuality.

Brought into existence through €5 million of seed funding from Baden-Württemberg's state government, the TAF BW started its operations in 2018 (TAF BW, 2024c). Operated as a state-sponsored on-road AV trial between the mid-sized towns of Karlsruhe, Heilbronn, and Bruchsaal in south-west Germany, the TAF BW makes extensive use of HD maps and marks one of the most advanced AV implementation sites in Germany. The central idea of the project is to provide public and private AV developers with a real-life environment for the testing of autonomous and connected vehicles fully embedded within the region's ordinary traffic. To this purpose, more than 250 kilometres of the street and road infrastructure within the urban triangle of Karlsruhe, Heilbronn, and Bruchsaal – from inner-city crossroads, to highways, to rural roads – were integrated into the TAF BW's designated test area. Following state-of-the-art procedures, these sections, including important details such as traffic lights, street signs, types of street boundaries, reflector posts, and more, were then HD-mapped (TAF BW, 2021: 4). Contrary to the corporate-led HD-mapping operations of Waymo and other US companies, TAF BW is, first and foremost, a state-driven initiative. Yet, the technology underlying its HD maps is comparable to the former. As a staff member of Karlsruhe's transit agency, the Karlsruher Verkehrsverbund (KVV) elaborates, 'You can imagine it as follows: We first drove through with a sort of Google Maps vehicle [...] and mapped everything in high definition' (interview, 29 February 2024).[7] Marking one of TAF BW's central safety requirements, HD mapping has been at the core of the project from the very start.

The following exploratory analysis of TAF BW and its latent conflicts is based on an ethnographic research approach (Crang and Cook, 2007). First, qualitative content analyses of website material and official documents linked to TAF BW provided the basis of my explorations. These were complemented, second, by two expert interviews with local employees involved in the project: a senior staff member of the KVV, on the one hand, and an employee at Karlsruhe's Research Center for Information Technology (Forschungszentrum Informatik, FZI) on the other. Third, I conducted participatory observations and ad hoc conversations at Messe Hannover 2024, where the FZI exhibited its 'CoCar' AV prototype. Finally, a two-day field stay in Karlsruhe in May 2024 that included exploratory walks and field-site photography of TAF BW's actual road infrastructure rounded out my ethnographic explorations.

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[7] Interviews were conducted in German; interviews and non-English quotations have been translated by the author.

Latent conflicts of governance

Contrary to the more privately driven HD mapping exercises of companies such as Waymo or Cruise in the US, the TAF BW is run by a complex network of local and regional governments, public agencies, and research institutes (TAF BW, 2024b). While integrated by a common interest to develop TAF BW as one of Germany's leading projects of AV implementation, its diverse set of actors also brings with it a number of diverging goals, strategies, and priorities. These can be understood as latent conflicts of governance that, while not always fully visible, are inherent to TAF BW's complex governance structure: First, acting as the core funder of TAF BW, the state government of Baden-Württemberg pursues what can be called an extrospective policy strategy that harnesses TAF BW as a flagship project to showcase the region's global competitiveness in the field of automotive manufacturing and tech innovation (Wiig, 2015). One of the government's recent strategy papers nicely illustrates this agenda:

> The automotive industry in Baden-Württemberg is at a crucial turning point. As one of the industry's most important locations worldwide, Baden-Württemberg is particularly affected by the profound changes driven by electrification, digitalization, and automation. [...] It is crucial for Baden-Württemberg to understand these changes and adapt to them in order to remain competitive in the future. (SDA BW, 2023: 17)

In contrast, Karlsruhe's local transit agency, the KVV, can be said to pursue a more 'introspective' agenda, harnessing TAF BW as a technical-cum-institutional vehicle for the digital modernization of its local transport offers. For instance, the transit agency has started to operate autonomous minibus shuttles in select areas of the test field that serve as last-mile feeders in the small neighbourhood of Weiherfeld-Dammerstock (KVV, 2024). While the KVV's ambitions of infrastructural modernization are not necessarily incompatible with the development plans of Baden-Württemberg's regional government, the diverging scalar and strategic orientations of the two actors – extrospective globalism versus introspective localism – are indicative of latent tensions at the level of TAF BW's overarching governance structure. Further complicating the picture, there are five local research institutes involved in TAF BW: the FZI Research Center for Information Technology, the Karlsruhe Institute of Technology (KIT), University of Applied Sciences Karlsruhe (HKA), Heilbronn University of Applied Sciences (Hochschule Heilbronn), and the Fraunhofer Institute of Optronics, System Technologies and Image Exploitation (IOSB) in Karlsruhe. Many of these institutes have used TAF BW in coordination with their own partly independent research projects. For instance, while CoCar, the FZI's AV prototype, is closely linked to TAF BW, it is licensed to be used in the entirety of Germany, and not only within TAF BW's much more restricted area. The scalar orientations of semi-independent research projects within TAF BW can differ substantially, adding to latent tensions within its governance structure.

Furthermore, the local governments of Karlsruhe, Bruchsaal, and Heilbronn find themselves in a mediating position between the – far from always fully congruent – goals of Baden-Württemberg's government, the KVV, and the involved research institutes on the one hand and the political communication of these diverse strategies and aims to local citizens on the other. As reported by a KVV staff member, in Karlsruhe, citizen reaction to the test field was not always fully positive: 'You have to imagine, when we started to build up the test field, the municipal administrator of one part of town immediately came to us and said: "Well, are the children in our nursery still safe? Can I send them to the nursery alone? Can I let them cross the street alone?"' (interview, 29 February 2024). In reaction to these and other concerns, a citizen forum was held several months prior to TAF BW's official start in late 2017. Again, a full spectrum of sentiments – from strict opposition to full endorsement – was present: 'Everything was there – from total opponents, rejection, almost getting violent, to those who say, "Well, great, wonderful, when will it start?"' (interview, KVV staff member, 29 February 2024). It is at the level of local municipalities that conflict and active citizen opposition have become most manifest in the context of TAF BW and where existing concerns are being addressed via public consultations.

In sum, given the diverse set of actors steering TAF BW, it is fair to say that latent conflicts of governance have been inscribed in the project's DNA from the start. Although to some degree integrated by a long history of automotive manufacturing and excellence in tech-sector research in the region, the diversity of actors involved in TAF BW's governance structure brings with it not only diverging strategic interests and scalar orientations but also persisting conflict potential with regard to the shaping of the region's mid- to long-term future.

Latent conflicts of regulation

Latent conflicts of regulation are similarly prevalent within the TAF BW project. Next to safety aspects and technical requirements governed by Germany's 2017 Act on Autonomous Driving and the Vienna Convention on Road Traffic, data regulation is one of the most contentious, yet largely invisible, issues at the heart of TAF BW. In line with recent efforts to regulate data security on supranational scales (Stark et al., 2021), TAF BW follows the EU's 2018 General Data Protection Regulation (GDPR) as one of its central guidelines (TAF BW, 2018). While usually regarded as providing stricter data security and anti-surveillance regulations than analogous frameworks in the US (Guay and Birch, 2022), the GDPR does allow the mass collection, storage, and later analysis of data by large-scale corporate and state actors as long as this data is anonymized.

As a closer look at the aforementioned CoCar project of the FZI indicates, however, even formal compliance with existing data regulations does not foreclose deeper and partly hidden levels of regulatory conflict. Equipped with 12 LIDAR systems, 9 full-HD cameras, 3 radar sensors, and more (FZI, 2018), the current generation of the FZI's CoCar is able to collect detailed data of its spatial environment that may be channelled both into HD maps and AI training data. Beyond the CoCar's mere technical capabilities, however, it is the data rights provisions underlying the project that tell an insightful story of defused regulatory conflict. Consider, for instance, the following situation: The CoCar prototype passes by and captures on its video system a nearby pedestrian coincidentally walking past the car. Provided this person is aware of the situation and the fact that they might have been video-scanned, they might catch a closer look at the vehicle and be able to photograph a sticker attached to the car's rear fender (Figure 2).

Figure 2: Latest generation of the FZI's CoCar prototype, exhibited at Messe Hannover 2024. The sticker above the rear fender provides a QR code that links to the FZI's privacy policy webpage.

Source: Author.

This sticker provides crucial information regarding the person's data rights: Above a caption reading 'data protection for autonomous driving', the sticker shows the symbol of a surveillance camera, the logo of the FZI, and a QR code that leads to the FZI's privacy policy webpage. On this webpage, one finds a brief text that explains the AV project's use of data, including the following passage:

> The legal basis for processing the video files of the environment of the test vehicles is our legitimate interest, pursuant to Art. 6 (1) lit. f GDPR [General Data Protection Regulation]. The legitimate interest of the FZI for processing these video recordings derives from the interest of operating the test vehicles and for researching connected, semi-automated, and autonomous driving functionalities. (FZI, 2024a: n.p.)

Next, if one follows through to the GDPR, article 6 (1), one finds a number of conditions under which the processing of personal data is allowed under this framework. As stated under clause (f), the passage referred to by the FZI's privacy policy, the processing of personal data is allowed if

> processing is necessary for the purposes of the legitimate interests pursued by the controller or by a third party, *except where such interests are overridden by the interests or fundamental rights and freedoms of the data subject which require protection of personal data, in particular where the data subject is a child.* (GDPR, 2024: n.p.; emphasis added)

Interestingly, and invisible from the FZI's abridged reference to it, clause (f) of article 6 (1) in the GDPR juxtaposes the interests of a data collector (in this case: the FZI) with the fundamental rights of 'data subjects' (our imaginary pedestrian). While formally in line with the GDPR, a closer look at the latter betrays significant differences between the (already hard-to-track) data rights information provided by the FZI on the one hand and the actual formulations and provisions of the legal text on the other. To return to the starting point of our street scene from above: The fact that our imaginary pedestrian possesses fundamental privacy rights that may in fact override the data-collection interests of the FZI's CoCar project is hardly visible from an everyday standpoint. Rather, this fundamental yet largely hidden regulatory conflict is buried, deliberately or not, beneath several layers of hard-to-track data rights information and oblique legal jargon.

Latent conflicts of imagination

Third, the case of TAF BW is indicative of latent conflicts of imagination at the heart of autonomous driving in general and HD mapping in particular. As scholars in the field of science and technology studies have long pointed out, technological innovations tend to come with different socio-technical imaginaries that foreground various, often competing, dimensions and potentials of a new technology (Jasanoff and Kim, 2015). Particularly in cases in which the societal impacts of emerging innovations are still in early formation, one usually finds severe 'competition over imaginaries as different stakeholders promote different visions in policy and political discourse' (Guay and Birch, 2022: 3). As with many other concurrent projects of HD mapping and AV implementation, one of the prevalent visual imaginaries of TAF BW is that of 'machine vision': the urban landscape perceived through the multisensory eyes of the self-driving car.

Consider, for instance, a short video (TAF BW, 2024a) available at TAF BW's website that explains the machine vision and motion planning of the earlier S500 AV prototype developed by Daimler in cooperation with the FZI and KIT (KIT, 2013). While the left side of the video shows an on-board roadside view similar to that of a real driver, the right side of the screen displays the same situation from a bird's-eye perspective (Figure 3). In contrast to the driver's view on the left side, the overhead view includes various layers of additional information visualized through overlaid geometric forms of different colours and shapes: For instance, while the AV's own position is indicated through a small car symbol at the centre of the top-view scene, road-side objects such as parked cars or passers-by are visualized as moving pink dots; street limits are shown as continuous slim lines (red for left, green for right), and the AV's near-future trajectory is projected ahead of the car symbol as a moving line of small circles of various colours, which represent the varying time differences of the car's projected near-future position(s) in relation to its present location. Two orange polygons further delimit the drive corridor around immediate obstacles – in this case, two parked cars. The projected trajectories of oncoming vehicles, meanwhile, are equally visualized through shape-shifting lines of coloured circles. While the shifting meaning of all of these visual signifiers may variously exceed the capacities of the human eye and intellect, these signifiers are there exactly for this purpose: to render visible to the human viewer the spectacle that is going on 'inside' the black box of the self-driving AI.

Parallel to a plethora of similar visual materials currently produced and circulated in the context of HD mapping and autonomous driving (see e.g. Waymo, 2021), TAF BW's video can be understood as a sequence of 'operational images'[8] (Parikka, 2023): images that are not needed by the machine itself but whose main purpose is to make the machine's 'internal' operations more understandable for the human viewer. 'Machines,' as Trevor Paglen explains, 'don't need funny animated yellow arrows and green boxes in grainy video footage to calculate trajectories or recognize moving bodies and objects. Those marks are for the benefit of humans – they're meant to show humans how a machine is seeing' (2014: 73). Who then are the human addressees of TAF BW's video? We may think here of three groups, each somewhat wider in extent than the one before it. First, it is not unlikely that the researchers

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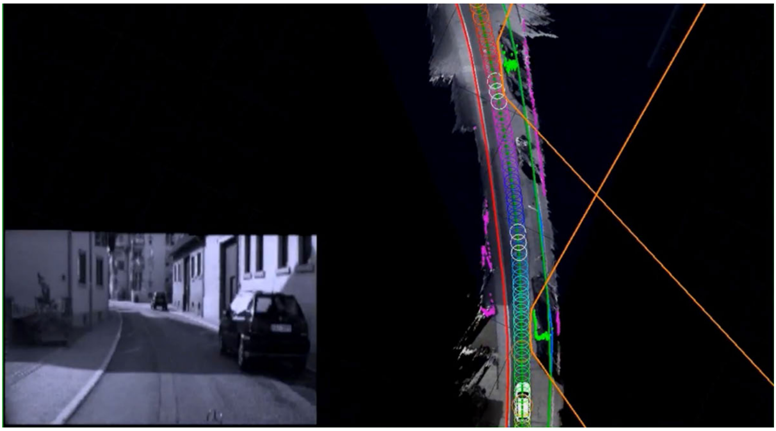
[8] The term was coined by the filmmaker and theorist Harun Farocki (Paglen, 2014).

of the S500 prototype project themselves might have relied at times on visual aids identical or at least similar to those exhibited in the video. Second, it is fair to assume that one of the video's main 'target audiences' is comprised of exactly those personae that in the context of this chapter I referred to as professional space-makers, to wit: urban planners, political decision-makers, public officials, policy 'experts', regulators, and more. Third, and accounting for the fact that the video is openly available on TAF BW's webpage as well as on YouTube, videos such as the one discussed here clearly also address the wider public 'as such'. Particularly vis-à-vis this wider public as well as professional space-makers, the video's dominant visual language is of interest as it conveys – exactly *through* the visual overlay of simple geometric shapes and forms – a sense of absolute precision, calculability, and control that stands in maximal contrast to many of the prevailing uncertainties that I explored in the sections above.

Figure 3: Screenshot taken from video explaining the technology of the S500 AV prototype developed by Daimler in cooperation with the FZI and KIT.



Source: TAF BW (2024a). Image reproduced here with the kind permission of Forschungszentrum Informatik (FZI) Karlsruhe.

Conclusion: Studying autonomous driving and tech urbanism in context – What next?

As discussed in this chapter, procedures of HD mapping mark a primary site of urban future-making. Similarly to current practices of AV testing and trialling (Marres, 2020; Dowling et al., 2023), HD mapping can be understood as an attempt of making manageable the inherent uncertainties of the city's urban street life with its myriad of objects and subjects, both mobile and static. In this context, the HD map serves as one of the technologically most advanced instruments of urban risk mitigation. As I argued with recourse to the case of TAF BW, however, practices of HD mapping are themselves embedded within broader – often still 'black-boxed' – conflict constellations of contemporary tech urbanism: latent conflicts of governance, regulation, and imagination. Crucially, these three arenas of social struggle and ongoing political (re)negotiation are subject to historically path-dependent and spatially variegated trajectories of professional space-making in different urban settings worldwide (Robinson, 2011; Brenner, 2014). Within these differential and multi-scalar settings, closer *situated* engagement with the urban implementation of AVs in general and HD mapping in particular forms a vital field of both theoretically informed and empirically grounded critical urban research in the context of a multitude of 'actually existing' tech urbanisms (Shelton et al., 2015).

It is against this background that I want to make three brief methodological suggestions for further scholarly work on the nexus of autonomous driving and HD mapping. First, I see it as one of the most pressing tasks for critical and radical urban scholarship to relate these phenomena *to*, and make them intelligible *within*, both wider and longer existing contexts of urban future-making worldwide: contexts of planetary urbanization that continue to shape the very conditions of existence of 'the' tech city itself (Brenner, 2014). Such 'horizontal widenings', second, should not and need not exclude equally paramount 'vertical' orientations towards analytical depth and empirical detail. In this respect, Susan Leigh Star's (1999: 383) time-honoured plea for an ethnography of infrastructure 'capable of surfacing silenced voices, juggling disparate meanings, and understanding the gap between words and deeds' still has much to offer in the face of dangerously narrow and oftentimes outrightly techno-determinist visions of the urban future (Mattern, 2021). Finally, echoing Shapiro (2021), there is a need to look beyond tech capitalism's more visible end-user products as *things* (AVs, drones, robots, and more) and engage with the often more inaccessible *processes* that underlie these eventual use cases. HD mapping, as this chapter aimed to show, marks only one of these more deeply buried and still widely black-boxed procedures at the heart of current urban future-making.

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