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Maps and the Autonomous Vehicle as a Communication Platform

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Over the past two decades, there has been growing awareness of and critical interest in the convergence of information and communication technologies and automobiles. Writing in 2004, Mike Featherstone suggests that the "automobile becomes a new form of communications platform with a complex set of possibilities." In this article, we argue that the notion of the car as a communication platform continues to form a productive way of thinking about autonomous vehicles. The argument we develop is that the dual roles of data acquisition and management, and local processing are integral to any understanding of the contemporary autonomous vehicle's "machinic complex." Both of these things are strongly associated with autonomy and the transformation of cars into decision-making machines. We use the example of mapping to argue that these capacities are not unique to the emerging technologies of autonomous vehicles; however, they are essential to them, with significant implications not only for their capabilities as communications platforms, but also more generally for their governance and political economy.

Keywords: autonomous vehicles, communication platform, maps

> The desire to be free from the constraints of driving demands being tied into communication networks. (Hay & Packer, 2004, p. 225)

At the 1956 edition of Motorama, General Motors' (GM's) famed U.S. touring auto show, the company launched its latest concept car (or "laboratory on wheels"), the Firebird II—a gas-turbine-powered four-seated family sedan with airplane-type styling and a transparent canopy roof. Accompanying the Firebird II was a promotional brochure, "The Story of Firebird II" (see Figure 1), and a short film, *Key to the Future*, introducing GM's "dramatic and daring concept of a Highway of Tomorrow" where automated cars followed electronic directional control strips embedded in the road.

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Figure 1. The cover of the promotional booklet promoting General Motors' 1956 concept car, or "laboratory on wheels," Firebird II (https://mattsko.wordpress.com/2013/02/28/1956-firebird-ii-concept-car/).

Key to the Future depicts a futuristic scenario of a family of four traveling on vacation in their new Firebird II. The occupants of the car, in consultation with a highway operator situated in one of many Autoway Zone control towers, select their destination and determine their route after viewing map information sent to their dashboard screen by the highway operator. Once these decisions have been made, the driver cedes control of the car to an "electronic brain" that automates the rest of their journey as they relax in comfort (King Rose Archives, 1956/2013). The console of the Firebird II acts as a communications center, in which there is a "Dashboard View screen" consisting of a left and a right panel:

> The left panel is for "internal communication" between car and driver. . . . It also reveals a radar pattern when [the driver] guides the car on the electronic control-strip for automatic steering. "External communication" from the control tower in his Autoway Zone also appears on this panel. The right-hand panel supplies normal television reception, and two-way television communication with motels, other cars, etc. ("The Story of Firebird II," 1956, p. 13)

None of the features described in the brochure were operative in the Firebird II (or its 1958 successor, Firebird III). Rather, "they serve[d] merely to complete the demonstration of how an electronically controlled car should be equipped" ("The Story of Firebird II," 1956, p. 13).

Although GM's vision for the Firebird II remains imaginary, over the past few decades, there has been growing awareness of, and burgeoning critical interest in, the confluence of media and communication technologies and automobiles. This interest takes in Jean Baudrillard's much-cited formulation from the 1980s that the vehicle has become a bubble in which the dashboard is a console and where "the landscape all around unfolds as a television screen" (Baudrillard, 1987/1988, p. 13), explorations of the car *as* a communication technology (Giblett, 2000; Sachs, 1992), and a sharpened critical focus around concern for the automobile as a site where communication, mobility, and sociability converge (Bachmair, 1991; Featherstone, Thrift, & Urry, 2005; Goggin, 2012; Hay & Packer, 2004).

Writing in 2004, Mike Featherstone (2004) observed that the "automobile becomes a new form of communications platform with a complex set of possibilities" (p. 8). For Featherstone, these possibilities include the opening up of a number of different lines of communication. One line of communication involves interactions, via various transparent and reflective media (windshield, windows, mirrors), between the driver and other drivers. Another involves mediated forms of communication (e.g., mobile phone, mobile Internet) that exit the automobile, linking its occupants with distant others. Still another involves communication and entertainment media, such as radio or television or other recorded media (on smartphones, CDs, and tapes), entering the automobile. In these ways, the automobile as a communications platform combines "media/communication and mobility/transportation [in ways that] have become integral to one another" (Hay & Packer, 2004, p. 212).

In their book *Racing the Beam: The Atari Video Computer System*, Nick Montfort and Ian Bogost offer a somewhat different and quite specific conception of "platform" as the "hardware and software framework that supports other programs" (Montfort & Bogost, 2009, p. 1). This definition is apposite to the present discussion of the automobile as a communications platform for the reason that "software, in its many manifestations, has become an integral element of the mechanics of cars" (Thrift, 2004, p. 50). As Nigel Thrift (2004) explains,

> Now software controls engine management, brakes, suspension, wipers and lights, cruising and other speeds, parking maneuvers, speech recognition systems, communication and entertainment, sound systems, security, heating and cooling, in-car navigation and, last but not least, a large number of crash protection systems. Almost every element of the modern automobile is becoming either shadowed by software or software has become (or has been right from the start, as in the case of in-car navigation systems) the pivotal component. (p. 50)

Thus, for the automobile as a communications platform, it is not just the "complex of communication and transportation technologies" (Hay & Packer, 2004, p. 217) that matter, but, ever-increasingly, computation as well, a point that will prove crucial to the later arguments of this article.

With the emergence of autonomous vehicles developed by Google, Uber, Baidu, and others, there has been a further reinvigoration of critical interest in cars as communication platforms. Contemporary autonomous vehicles have far greater capabilities than the cars Featherstone wrote about, but they appear to fall generally within his formulation of the "car-driver-software assemblage" (p. 10), where "the governance of the car is increasingly delegated to the machinic complex" (p. 10; see also Sheller & Urry, 2000, p. 738). John Urry (2004) describes this "assemblage," or "machinic complex," as a combination of "specific human activities, machines, roads, buildings, signs and cultures of mobility" (p. 26), among other things, that collectively form what he terms an "automobility system" (Urry, 2007, p. 115). What is key to this system, to this assemblage, he writes, "is not the 'car' as such but the system of fluid interconnections" (p. 26). Structuring the "automobility system," Urry (2007) argues, are vital interconnections with numerous "interdependent systems of 'immobile' material worlds" (pp. 53–54) and infrastructures, including transmitters, roads, garages, and so on.

What we thus see as most striking about the historical example of Firebird II with which we opened this article is not (only) that it anticipates contemporary fascination with autonomous vehicles by several decades, but also that GM's vision of an automotive future is one of an "automobility system" that clearly combines media and communication technologies, maps and maps data, automated vehicle systems, and extensive supporting network infrastructures.

In this article, we consider the ramifications of Featherstone's and Urry's notion of cars as communication platforms for autonomous vehicles. Our argument is that this notion remains a useful frame for thinking about the contemporary settlement of autonomous vehicle technologies, but that these communications platforms operate in ways that have intensified significantly since the time of their writing. As vehicles become increasingly automated, they necessarily become more dependent on communication systems—especially, we argue, maps and location data because, above all, what the autonomous vehicle is communicating is its position. Autonomous vehicles now operate as nodes in an array of networks, addressing local, cellular, and satellite systems. Among the most important of these are machine-to-machine communications linking vehicles to each other (vehicle-to-vehicle, or V2V, communication), to infrastructure (vehicle-to-infrastructure, or V2I, communication), and to the Internet of things. In addition, there are cloud services providing data processing and management, aggregating and analyzing telemetric data. As Deb Miller Landau (2017) writes, "While each car is an individual vehicle, it will actually become part of a complex ecosystem where communication—how cars talk to other cars, to road-side infrastructure, the network and finally data centers—is key" (para. 8).

However, although these forms of networked communication are essential elements in the contemporary "machinic complex" of the autonomous vehicle, an emphasis on that aspect risks missing the significance of two other areas of functionality critical to the governance of autonomous vehicles: first, the work of the vehicle as a prodigious collector and producer of data, and second, the vehicle's capabilities for processing those data as well as communicating information about them. Autonomy, in vehicles as elsewhere, involves predictive, decision-making functions, requiring large amounts of data and information. Autonomous vehicles now work constantly to locate themselves and other objects in their immediate environments. They rely on cameras, a range of specialized sensors, and detailed mapping information. Even today's production vehicles, with limited autonomous capabilities, are estimated to generate around six gigabytes of data every 30 seconds, acquired through cameras and radar systems (Stewart, 2018). Autonomous vehicles also need to make decisions in real time, which requires a high level of on-board processing capacity and a practical division of processing labor between the car and the cloud. Local processing is highly sophisticated, as autonomous vehicles rely on machine learning and deep learning to recognize proximate objects.

These aspects of the vehicle's "machinic complex"—the integral roles of data acquisition and management, and local processing—may be strongly associated with autonomy and the transformation of cars into decision-making machines. In this article, we use the example of mapping—a comparatively unexplored aspect of motor vehicle history—to argue that these capacities are not unique to the emerging technologies of autonomous vehicles, but essential to them, with significant implications not only for their capabilities as communications platforms, but also for their governance and political economy more generally. Our argument in this section is that maps constitute a vital, yet largely neglected, aspect of the contemporary "automobility system" in which the vehicle functions as a communications platform. Maps are also interesting in light of Featherstone's earlier lines of communication in that they both *enter* the vehicle (communicating location information *to* the driver) and *exit* the vehicle (communicating location information *about* the driver and the vehicle).

In the first part of this article, we provide some historical context. We trace a series of key points in the development and gradual incorporation of maps into automobiles to explain the central place that this particular kind of data has had in the development of human control of vehicles, and now in autonomous vehicles. Building on the historical analysis, in the second section of the article, we argue that, such is the importance of maps data to autonomous vehicle development, access to data has become the focus of intense competition. We explore the case of Uber and its struggles to acquire mapping data—struggles that are intimately connected with its autonomous vehicle ambitions. Third, we position the place of mapping data alongside other rapid technological innovations related to mobile and autonomous vehicle navigation, including LIDAR, and V2V communication systems. We show how these combined data streams sit at the heart of the contemporary configuration of autonomous vehicles as communication platforms. Fourth, we show how this combined suite of mapping and associated navigation capacities interacts with and is reliant on wider infrastructures, including mesh networks and urban-situated sensor systems, to create what software engineers in this field refer to as an "Internet of autonomous vehicles" (or V2I communication), a configuration with the potential to carry a complex set of possibilities as well as regulatory and other challenges. Finally, we conclude by sketching the implications of our argument for the problem of regulation and governance of autonomous vehicles as well as their impact on transport industries. Without an enlarged view of the automobile as a communications platform, it will be very difficult to come to grips with the public policy and political economy questions that autonomous vehicles pose.

Histories: Rethinking the Automobile as a "Communications Platform" With Maps

Our conventional understanding of the automobile as a communications platform emphasizes media and telecommunication, drawing on, for example, Raymond Williams' (1974/1992) idea of the development of the car as a form of "mobile privatization," "that which served an at once mobile and home-centred way of living" (p. 20). Within the modern automobile, Kurt Möser (2003) notes, the car dashboard and passenger cabin can "be interpreted as a 'user interface' of a complex mobility machine" (p. 61) that functions "as a crossover between [a] 'cockpit' and [a] fast yet intimate living room" (p. 79)—sentiments that echo Roland Barthes' (1993) famous observation that the dashboard of the Citroën DS19 "looks more like the working surface of a modern kitchen than the control-room of a factory" (p. 89). The incorporation of entertainment media into the car has been central to this vision, with the introduction of commercial in-car radio in the United States from 1930 (Berkowitz, 2010). Ever more sophisticated media systems have followed—not least among them the short-lived "Highway Hi-Fi" project from the late 1950s, a collaboration between Chrysler and Columbia Records to develop in-car phonograph players (OOK World, 2017). This collaboration included a pre-digital rights management arrangement, ensuring that "drivers could only listen to artists signed to Columbia Records" (Massy, 2007).

The long incorporation of technologies for telephony into cars is now well known. Before the emergence of mobile cellular phones, mobile radio telephony was well established. In the United States, Bell Labs was testing this technology as early as 1924 (Farley, 2005), although it wasn't until 1946 that these devices were developed commercially (Farley, 2007; for detailed history, see Fors, 2016). Related systems were also in operation elsewhere, such as "Air Call" in the United Kingdom, made famous in Michelangelo Antonioni's (1966) film *Blow-Up*; "you made a radio call [from your car] to a central operator who would in turn make a phone call for you and relay the conversation both ways" (Hooton, 2010, para. 7). It is also worth noting here that radio communication played a pioneering role in the early history of autonomous vehicles, where it was used in 1925 to control a driverless car from a car following close behind (Green, 1925).

Jumping forward to the 21st century, the car has become a sophisticated communications and entertainment hub, with vehicles "increasingly hybridized" and incorporating the technologies of the mobile phone, personal entertainment systems, and computing (Hay & Packer, 2004; Sheller, 2004; Urry, 2004). With the development of autonomous vehicles, the automobile becomes not just a communication and entertainment hub, but also a base—a platform—on which other applications, processes, and technologies are developed and operate.

Within historical accounts of the automobile as a communication platform, recent work has begun to examine the long and complex convergence of cars and maps (French, 2006; Goggin, 2012; Lendino, 2012; Newcomb, 2013; Thielmann, 2007, 2016; van Echtelt, 2014). Revisiting this history is important here: It involves some necessary revisions in our received understanding of the automobile as a communication platform, from a system primarily involving entertainment media, information display, and telephonic communication to one that emphasizes communication and information capture and processing with the surrounding environment for the purposes of navigation and control.

Cartographic information and communication (Guelke, 1977; Robinson & Petchenik 1975) in the form of road maps, atlases, and directories constituted an essential in-car accessory from the very earliest days of automotive transport—"almost as soon as it hit American streets in 1896, automobile advocates began testing the geographical limits of the car" (Akerman, 2006, p. 167; on the longer history of road maps, see Delano-Smith, 2006). These maps—as well as other media, such as photo-auto guides, which combined textual and other instructions with landscape photography and maps in published books (Thielmann, 2016)—were both sources of vital information and eloquent symbols of the power and possibilities associated with mobility. Maps were necessary because automobiles (to a greater degree than, for example, horses) were entirely dependent on the existence of special road infrastructures—a widely recognized limitation of the new technology of automobiles—but they conveyed great capabilities for long-range travel and urban convenience. Ackerman (2006) and French (2006) show how automotive maps were produced by organizations at the strategic centers of power in the motor vehicle industries, from oil companies (Ackerman, 2006) to automobile clubs (French, 2006).

The mechanical control of maps was seen as a necessary early step in enhancing the control of motor vehicles. In-car mechanized maps—or "mechanical guidance systems," as French (2006, p. 267) refers to them—appear early in this history. One of these, the Chadwick Road Guide from 1910, consisted of a metal calibrated disk with holes punched into it that were spaced to coincide with decision points along the specified route, and where the disk rotated "in synchronization with distance traveled" (French, 2006, p. 269). Another, the Jones Live-Map from 1911, "consisted of a turntable slowly rotated by a gear train connected to one of the vehicle wheels by a flexible shaft" (pp. 268–269; see Figure 2).

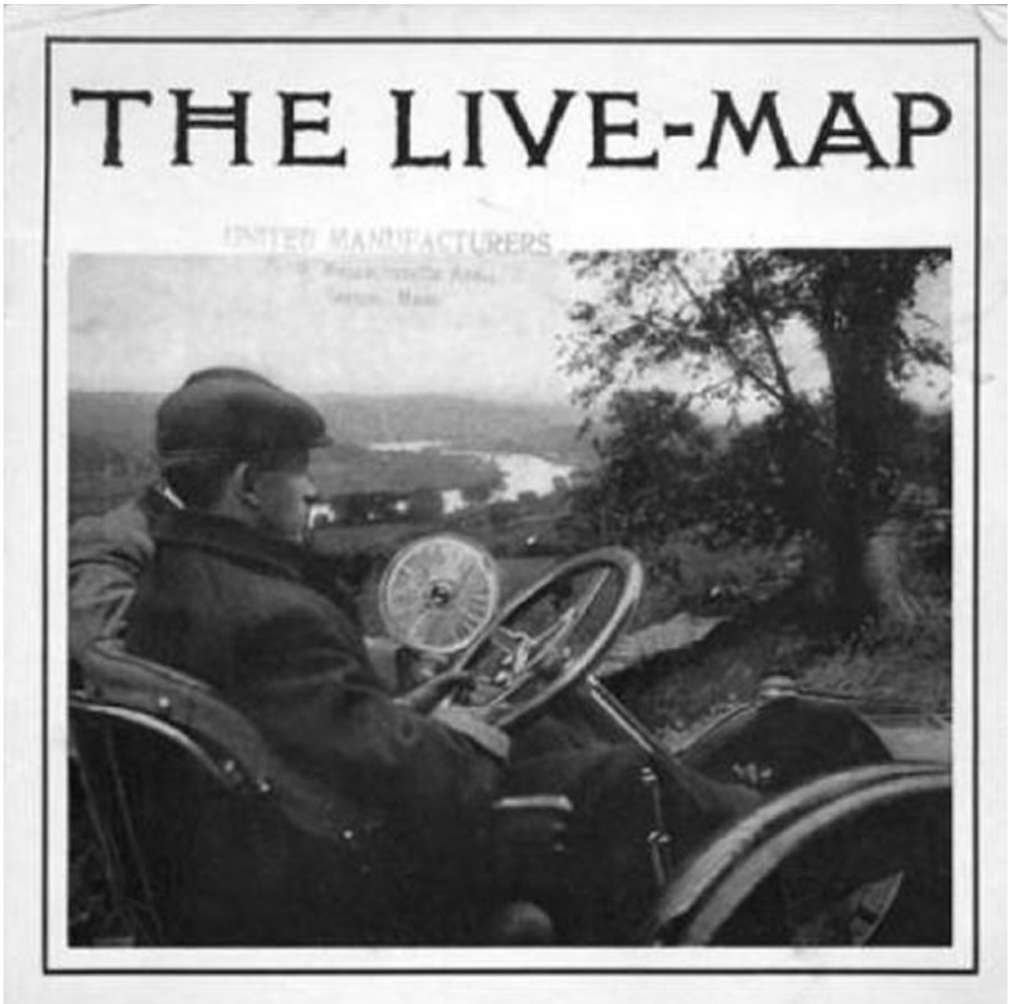

Figure 2. The Jones Live-Map, 1911 (http://factlets.info/JonesLiveMap).

Related technology appeared, ca. 1930, in the form of the Italian-made Iter Avto (see Figure 3). This was a dash-mounted device containing a scrolling paper map that was loaded into the system to correlate with a specific route. The map was wound from one roll to another across a display and was "linked to the speedometer with a cable, thus scrolling through . . . at a rate that was proportional to the vehicle's speed" (van Echtelt, 2014, p. 25).

Figure 3. The Iter Avto map, ca. 1930, with scroll winders visible at left (https://www.lomography.com/magazine/79074-iter-avto-the-worlds-first-gps-like-navigation-system).

A similar, if more rudimentary, scroll system—which predated the Iter Avto by a few years and Apple Maps on the Apple Watch by almost a century—was the Plus Four Wristlet Route Indicator from 1927 (see Figure 4). Worn on the arm like a wristwatch, miniature paper map scrolls were fitted to the device and then rolled across a face by twisting two small knobs. The Plus Four "is thought to be the first navigation device for motorists, without being built into the car itself" (Enoch, 2012, para. 13). It came with sets of map scrolls, with each scroll depicting set routes, "such as London to Bournemouth [or] London to Edinburgh, and the driver [wound] the knobs to move the map on as their car travels further" (Enoch, 2012, para. 15).

Figure 4. The Plus Four Wristlet Route Indicator, 1927, with accompanying miniature scroll maps (Chan, 2010).

A major step toward the development of modern, digital in-car navigation systems came with the creation of the Automatic Route Control System (ARCS), designed in 1970–1971 by the U.S.-based Command Systems Corporation. ARCS was the "first autonomous route guidance system to use an on-board digital computer with digitized maps and map-matching software in conjunction with a dead-reckoning subsystem" (French, 2006, p. 272). ARCS achieved this by employing an "electronic differential odometer for dead-reckoning and used map-matching software to correlate the apparent vehicle route with the actual route map stored on a digital tape cartridge" (p. 272). At the time, development of ARCS was sponsored by the *Fort Worth Star Telegram* "for use in automating home delivery of the daily newspaper," but support for the scheme was scuppered by labor interests concerned by the looming loss of jobs for newspaper delivery workers as a result of ARCS (pp. 273–274)—concerns, of course, that are very much part of contemporary anxieties regarding the development of autonomous vehicle systems for potential fleet use by the likes of Otto and Uber (Ong, 2017).

It wasn't until the 1980s that commercially released in-car navigation systems, as we know them today, began to emerge, with Japanese carmakers leading much of this development. In 1981, Honda introduced the Electro Gyrocator, a cathode ray tube display mounted on the dashboard and based on "inertial navigation technology using gyro and mileage sensors" (Berger, 2017, para. 3; see Figure 5). This was followed in 1985 by U.S. firm Etak's cassette-loaded Navigator system, which used dead reckoning: the process of calculating one's position by estimating the direction and distance traveled (Edwards, 2015; Newcomb, 2013). From these pioneering efforts, further developments followed in rapid succession: the first CD-ROM-based navigation system in 1987; the first in-built GPS navigation system in 1990; voice-assisted GPS in 1992; a system using Differential GPS (DGPS) or enhanced GPS in 1997; and a DVD-based navigation system in 1998. Early portable devices, among them Garmin's StreetPilot, appeared the same year ("Automotive Navigation System," n.d.; Newcomb, 2013; Santiago, 2017; for critical discussion, see Thielmann, 2007). Perhaps the biggest change occurred in 2000, when then U.S. President Bill Clinton ordered the discontinuation of a U.S. Air Force–designed protective GPS feature called "selective availability," opening up more accurate GPS services for nonmilitary use (Sturdevant, 2012). This led to the proliferation of navigation-focused GPS-driven technologies, first in the form of portable devices developed by TomTom, Garmin, and others, and later as apps for smartphones (see Lendino, 2012; Newcomb, 2013).

Figure 5. An early in-car navigation system: Honda's Electro Gyrocator from 1981. (https://autoweek.com/article/technology/1981-honda-invents-first-car-navigation-system).

These examples show how mapping interfaces and devices, alongside entertainment media, became integral to the automobile as a communications center. Given the specific and far greater navigational requirements of autonomous vehicles, precision mapping data have become a prized resource. With rapid recent developments in autonomous vehicle technologies, the tech firms and automobile makers responsible for driverless vehicles have begun to appreciate the importance not just of integrating maps interfaces into automobiles, but also of controlling, where possible, the data flowing through and feeding into these interfaces. We now turn to these efforts at exerting greater control over maps data.

Maps Data: Seeking a Scarce Resource

In examining why precision maps and rich maps data are so prized by autonomous vehicle developers, we concentrate on one firm—Uber. Uber provides a good example here because its struggles over mapping data are closely tied to its struggles to compete in the automotive vehicles space.

Maps data are vital to Uber's operations and are seamlessly integrated into its smartphone app at all levels. For the end user, the ability to book an Uber ride and then track the position of the approaching car on a map is one of the key features of the app interface. For this to work, both for the app user, and in terms of back-end operation and analytics, Uber has to rely on extensive behind-the-scenes maps infrastructure maintenance, including the population of points of interest, up-to-date routing information, and so forth. Until the beginning of 2014, these mapping services were supplied mainly by Google and subsequently by a suite of firms. Keen to address this situation, Uber made its first corporate acquisition in March 2016, purchasing privately owned U.S.-based mapping software company deCarta for an undisclosed sum (O'Brien, 2015). This firm was founded in 1996 under the name Telcontar and became known as deCarta from 2006.

In its very early days, Telcontar's main focus was the automotive industry, where it provided "street map data management, compression, route-finding and rendering tools for the personal and vehicle navigation markets" ("Personal and Vehicle Navigation," 1999, para. 1) by "integrating vector maps with information drawn from a variety of real-time and service-based sources" ("Telcontar Announces Close," 2001, para. 4). Telcontar's point of difference was its proprietary software, which was built on what later came to be called, following the firm's rebranding in 2006, the deCarta DDS (Drill Down Server) Geospatial Platform. The Platform provided clients with full geospatial functionality, which means routing, vector maps, geocoding, reverse geocoding, proximity searches, geofencing, and so on. The proprietary software operating on this Geospatial Platform consisted of three elements. The first was the Rich Map Exchange (RMX), whereby all incoming geodata were converted into an exchange format, RMX, that allowed the company to keep up with changes in the formats different geodata providers used. Then these data were compiled into their Rich Map Format (RMF), thus ensuring compatibility of services and features. Sitting behind both of these was the Rich Map Engine (RME), which did data access, routing, spatial indexing, and dynamic customization. In combination, these Platform services were applied within a variety of different situational and business contexts, with the firm's products used "to provide emergency and concierge services for drivers and wireless Internet users, real-time traffic information, direction and maps to Internet users, and to support call centers during emergency dispatch" ("Telcontar Announces Close," 2001, para. 4).

This account of deCarta's (Telcontar's) services provides a strong indication as to why deCarta would be of interest to Uber. The numerous investments, acquisitions, and deals that the mapping company secured in the decade before its sale are also important for understanding why it was regarded as such a valuable asset. In 2001, Telcontar closed a US$23.6 million funding round, with strategic investments made by a number of companies—most notably, Wingcast Incorporated, a "telematics joint venture" between Ford Motor Company and semiconductor and telecommunications equipment company Qualcomm ("Telcontar Announces Close," 2001). At the time, then president of Wingcast, Harel Kodesh, saw in these mapping technologies a compelling vision of an automotive future based on real-time and contextually specific, locally focused, geocoded data provision. "Using these location-based services," Kodesh remarked, "drivers will receive help automatically in the event of an emergency, obtain real time traffic updates with alternative routes, and access directions to and information about nearby businesses such as gas stations or restaurants" (quoted in "Telcontar Announces Close," 2001, para. 3). This vision has since been realized to some extent with traffic route recommendations services, such as Inrix and Google's Waze, and is also of strong interest to Uber. In addition, in 2003, Telcontar completed a merger with Televoke, a company that developed software applications that "enable notification, tracking, and control of commercial and personal assets, such as fleet tracking and vehicle theft retrieval" ("Telcontar and Televoke Merge," 2003, para. 1). Also of note is that, at the time of its acquisition, deCarta's clients (as Telcontar had become) included Inrix, as well as Ford and GM.

Uber's purchase of deCarta formed the first of a succession of strategic investments, partnerships, and talent and technology acquisitions between late 2014 and 2016. In December 2014, Uber announced a "strategic partnership" and investment arrangement with Chinese search giant Baidu—a deal widely viewed as necessary for Uber to succeed in the lucrative Chinese market. Having tested its service in Shanghai with an English-only service and reliance on Google Maps in 2013, Uber rapidly "upped its game," switching map providers, introducing a Chinese-language interface, and allowing users to pay using Alipay, Alibaba's equivalent to PayPal (Makinen, 2014). Ten months later, Baidu led a funding round that enabled Uber to raise an additional US$1.2 billion (Lunden, 2015a).

In 2015, Uber Maps recruited the former head of Google Maps, Brian McClendon, former Google Maps product manager, Manik Gupta (Hawkins, 2015), and one-time Google maps executive and angel investor, Daniel Graf, to bolster their mapping efforts. By mid-2015, Uber had purchased a sizeable portion of Microsoft Bing's mapping assets, along with 100 of its employees who had been working on image (including 3D image) collection—a clear indication of Uber's larger mapping infrastructure ambitions (Wilhelm, 2015).

Uber also purchased driverless truck firm Otto for US$680 million in mid-2016, a company cofounded by one of the original architects of Google's driverless car technology, Anthony Levandowski (Bhuiyan, 2016). The industry view seems to be that this last purchase was largely driven by a desire to hasten the development of driverless vehicle technologies, yet Uber's emergent logistics platform ambitions are also clear to see. However, with Alphabet's driverless car unit, Waymo, suing Uber following accusations that Levandowski stole intellectual property relating to Google's driverless cars (Wakabayashi & Isaac, 2017), the Otto purchase could prove a serious setback to Uber's autonomous vehicle and maps data ambitions.

In 2015, Uber (in a joint bid with Baidu) was hopeful of making a second key acquisition when Nokia signaled its intention to sell its maps arm, Here (Scott & Isaac, 2015). Nokia's mapping assets were built through a series of acquisitions, the most significant of these being the purchase of Navteq in 2007 for US$8.1 billion (Gale, 2015). Here was, however, not regarded as a high-performing division of Nokia's business, contributing only 3% of its overall valuation (Trefis Team, 2015). Further, the sale of Here would complete Nokia's strategic shift away from mobile phones and toward mobile wireless network equipment manufacturing following the sale of its handset-making arm to Microsoft for €7 billion in 2013 and the purchase of Alcatel-Lucent for €15.6 billion in 2015 (Dent, 2015). Nokia's willingness to part with its maps assets was a rare opportunity to gain control of one of the "big four" online mapping platforms (these being Google, TomTom, OpenStreetMap, and Here; Sawers, 2015). In addition to Uber and Baidu's joint bid, a long list of companies that were keen to bid for the Nokia-owned firm. This list is said to have included tech giants Apple, Facebook, Amazon, and Alibaba; private equity firms such as Hellman & Friedman; U.S.

broadcasting company Sirius XM Holdings; connected car systems firm Harman International Industries; and a consortium of German vehicle manufacturers (BMW Group, Audi AG, and Daimler AG [Mercedes]; Charlton, 2015). For maps analyst Gary Gale (2015), Uber's interest in bidding for Here was quite easy to explain: With deCarta, Uber now had "the platform to do geospatial calculations, such as routing, without relying on a third party," but it was still missing regularly updated maps data. Thus, for Gale (2015), the value for Uber of such an acquisition "is *less* about Here's mapping platform and much *more* about Here's mapping data" [emphasis in original].

However, the ultimate victor in this bidding war, paying €2.8 billion for Here, was the German consortium of car manufacturers. On one level, this seems a surprising outcome, given the strong interest from so many international tech industry heavyweights. On another level, however, the sale is far less surprising. Here was already a significant player in the automobile industry (more than half of Here's US$1 billion in revenue for 2014 came from that sector), with Nokia claiming at the time of the Here sale that it powered 80% of in-car GPS navigation systems (Sawers, 2015). Moreover, because all three members of the consortium already use Here Maps in their cars, the purchase of this mapping and navigation software and data from Nokia "enables them to retain full control—rather than allowing [it] to fall into the hands of a company such as Uber" (Sawers, 2015, para. 14) or Google (Bergen, 2018). A longer-term goal in making this purchase, it has been suggested, is for Here to create a more precise and accurate map that is closer to 1:1 scale, "which would ultimately make it usable for self-driving cars" (Trefis Team, 2015, para. 8).

The result of Uber's failed bid is that it has to rely on a blend of its own maps sources and those supplied by others (DeAmicis, 2015). Thus, in addition to drawing on Google Maps, Uber formed partnerships with TomTom to provide mapping and location services (Lunden, 2015b) and with high-resolution satellite imagery firm DigitalGlobe (which also provides services to Apple and Google; Golson, 2016). These last two deals were struck to improve the location data available to its drivers, not its customers. Uber is also said to be exploring options for placing "maps-generating sensors" inside the human-controlled cars in its service (Bergen, 2018).

For other automotive and tech firms with an interest in autonomous vehicles but without direct access to maps infrastructure, the development of precision maps has necessarily followed a different path. Toyota has decided to fit production cars with cameras and GPS units so that everyday drivers in their own cars, rather than drivers in specialist mapping cars, are logging data about "lanes, speed limits, signs, everything in the car's field of vision" (Collins, 2015, para. 2). Toyota argues that this strategy will create richer and more up-to-date maps than those created by specialized mapping cars laden with sensor arrays. However, it will require substantial data storage and processing capacities on board what are not autonomous vehicles. Baidu has taken the path of developing its own autonomous driving platform, called Apollo. In early 2018, Baidu announced a major upgrade to this platform, which included, among other things, "more HD mapping services available on a global scale," and support for major autonomous vehicle hardware developers Nvidia, Intel, NXP, and Renesas (Etherington, 2018, para. 1). Meanwhile, one year earlier, in 2017, semiconductor firm Intel purchased Israel-based company Mobileye for US$15 billion. Mobileye is "best known for automotive forward and rear facing cameras that capture imagery used in Advanced Driver Assistance Services (ADAS): things like collision avoidance, lane departure warning and adaptive cruise control" (Prioleau, 2017, para. 5). However, as maps analyst Marc Prioleau (2017) suggests, Intel plans to use Mobileye’s crowd-sourced sensor data to create “a continuously updating map called the Roadbook”:

> The Roadbook contains information about everything relevant about the road: the streets, the lanes, the buildings, signs and features that sit by the roadside and the data about how vehicles typically move through that environment. (Prioleau, 2017, para. 7)

The case of Uber reveals how highly prized precise digital road maps data have become to the “automobility system” of contemporary autonomous vehicle development. The control of mapping platforms and data is now seen not only as advantageous, but also increasingly as crucial to the successful communication platform development of autonomous vehicles.

Maps and Dynamic Data

Up to this point, we have argued for the vital importance of maps and maps data to autonomous vehicles. In practice, of course, the contemporary autonomous vehicle as a communication and information processing platform is fed an assortment of data from a variety of sources, all of which are vital for communicating the vehicle’s position in real time. Each autonomous vehicle must be able to perform the following operations at all times: orientation (where is it?), perception (what is around it?), and decision making (what should it do next?; Torres, 2015). Many tools perform these three actions.

Although the exact arrays of sensors and other technologies mounted on to or integrated into driverless cars differ from developer to developer, in general terms, these systems incorporate some combination of the following: video cameras, radar sensors, ultrasonic sensors, LIDAR (light detection and ranging) sensors, a GPS unit, and an on-board central computer. Video cameras are used to detect traffic signals, read road signage, keep track of other vehicles, and record the presence of pedestrians and other obstacles. Radar sensors, although not new to production cars (the 1959 Cadillac Cyclone used radar for obstacle detection; Jaynes, 2015), determine the position of other nearby vehicles, and ultrasonic sensors, which tend to be wheel mounted, are used to measure the position of close objects, such as curbs and other cars when parking. LIDAR sensors bounce pulses of infrared light off of surrounding objects, and these pulses are used to identify lane markings and road edges. GPS signals are combined with readings from other internal sensors and measurement devices (tachometers, altimeters, and gyroscopes) to provide positioning information. All these data are processed and actioned by the car’s on-board computer system, with algorithms and software, and linked with cloud data—vital for instantaneous decision making.

The array of tools here plays a crucial role in calculating orientation, perception, and decision. GPS is obviously a key means of determining orientation, as are radar, ultrasonic, and LIDAR sensors. However, because of the unreliability and inaccuracies of GPS signals and LIDAR sensor data, and the need for high-precision orientation information at all times—“an autonomous car that is 99% safe won’t be good enough” (Quain, 2017, para. 22)—driverless cars supplement this information with other data gathered from specific perception technologies, such as sophisticated cameras and other direct sensors. All these combined data are then processed within, and actioned by, the car’s on-board processors, which are linked to cloud servers, to make split-second decisions about car movement, navigation, and how to proceed.

Precision maps are vital at the orientation and decision stages of autonomous vehicle operation—"What HD maps give self-driving cars is the ability to anticipate turns and junctions far beyond sensors' horizons" ("High-Definition Maps," 2016, para. 7). The particular challenge for driverless cars, as autonomous vehicle development pioneer Sebastian Thrun explains, is to "map the environment while simultaneously determining the [car's] position relative to this map" (Thrun & Leonard, 2008, p. 872). "Key enablers" in responding to this challenge are what Thrun and Leonard refer to as "simultaneous localization and mapping" (SLAM) processes (p. 871), whereby the vehicle operates as a communication platform to combine, in real time, finely granulated precision maps information to orient the vehicle, with supplementary perception data generated from the vehicle's arrays of sensors, and with both sets of data continually interpreted and acted on, then reinterpreted and acted on, and so on, by the decision-making CPU.

Infrastructures and the Internet of Autonomous Vehicles

The "SLAM problem," as Thrun and Leonard (2008, p. 872) call it, signals an important idea: Autonomous vehicles can only function effectively where the environment "speaks back" to (communicates with) them as part of a continuously updating, dynamic urban map. Indeed, the importance of two-way, constitutive communication between vehicles (V2V) and the surrounding environment and supporting infrastructure (V2I) is by no means restricted to autonomous vehicles. As Porsche board member Philipp von Hagen points out, "connectivity between cars and infrastructure is one of the important megatrends in the automotive industry" (cited in Garnick, 2014, para. 4).

Infrastructures are commonly understood as a "system of substrates" ("railroad lines, pipes and plumbing, electrical power plants, and wires") that enables other things to happen (Star, 1999, p. 380). In a definition that is apposite for the present discussion of driverless cars, Brian Larkin (2013) argues that, at an even more fundamental level, infrastructure can be understood as "matter that enable the movement of other matter" and as "things and also the relation between things" (p. 329). Vehicles share with the wider mobile Internet their dependency on an extensive, purpose-built fixed infrastructure, all to enable the movement of individual elements at the edges of the network (see Featherstone, 2004; Packer & Crofts Wiley, 2012, p. 12; Parks & Starosielski, 2015; Sheller & Urry, 2000; Urry, 2004).

The importance of infrastructural support to autonomous vehicles, and communication between them, cannot be overemphasized and was grasped quite early in the development of driverless car technologies. For instance, and in addition to the vision for Firebird II, the Radio Corporation of America (RCA) and GM collaborated in the 1950s on the development of a driverless car system that involved radio-based communication between car and sensors embedded in roads (see Figure 6).

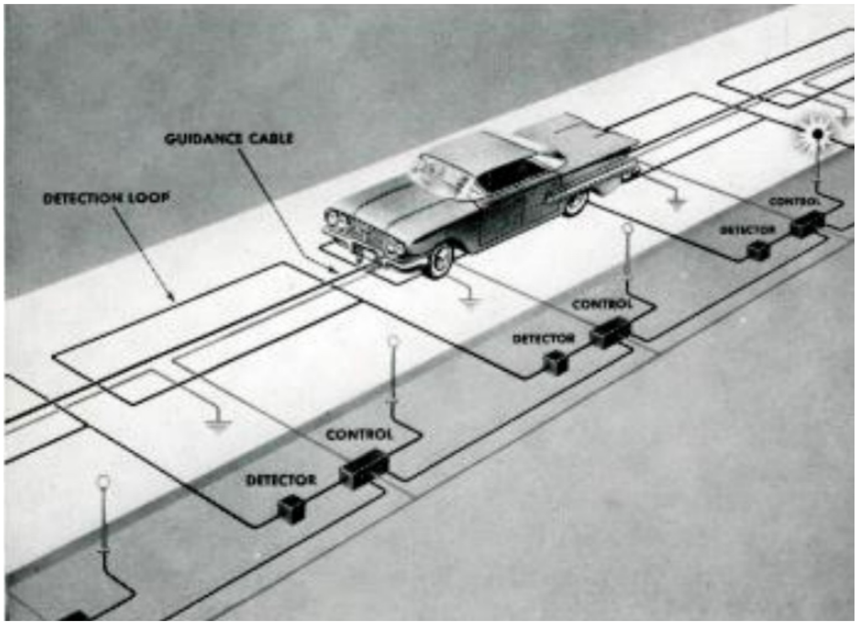

Figure 6. RCA and GM's Electronic Highway, showing the importance of infrastructural support to visions of autonomous transportation, with circuits buried beneath the pavement (Kilbon, 1960, p. 28).

This system is described as follows in a 1958 report for RCA's *Electronic Age* magazine:

> From beneath the pavement, electrical signals will radiate from buried wires to be picked up by the tiny transistorized receivers built into the car. On one frequency will come the signals from the guidance cable, controlling the power steering mechanism to keep the car in its lane. Signals on another frequency will warn of obstructions in the highway half-a-mile or a mile ahead—perhaps a stalled vehicle, or a highway maintenance crew at work. . . . Operating on a third frequency, the special highway receiver on the dashboard will pick up signals from a buried antenna and cut off the standard car radio to make an announcement of its own. ("Highway of the Future," 1958, pp. 12–13)

RCA demonstrated the system in operation at RCA Laboratories, and along a 400-foot (121-meter) strip of public highway on the outskirts of Lincoln, Nebraska, on October 10, 1957 ("Highway of the Future, 1958," p. 12). By 1960, RCA were touting the "commercial availability of the compact, all-transistor detector equipment which lies at the heart of the system," which they called Ve-Det, or Vehicle-Detector (Kilbon, 1960, p. 27). GM continued to work on this kind of car-infrastructure communications system throughout the 1960s, developing what it called Driver Aid, Information and Routing, or DAIR (Preston, 2013). A key aspect of DAIR was the "route minder," which worked as follows:

> For the route minder, the driver uses a special card punched for his destination. The card fits a slot in the console. The routing equipment is activated by signals from magnets buried in the road at each major intersection, and compares the signals with the punched instructions on the card. Panel lights will tell the driver whether to turn left, turn right, or go straight through. With all major intersections coded, it would be possible to travel across the U.S. by the system's direction. (cited in Preston, 2013, para. 9)

As with these early experiments, the "autonomy" of contemporary self-driving vehicles is a condition, as Urry (2004, 2007) noted a decade earlier in proposing his idea of an "automobility system" that can only occur within an array of supporting and overlapping infrastructures: cell towers, WiFi routers, networked sensors and actuators, external mesh networks, and cloud computing systems, as well as roads-related communications infrastructure (signs, signals, lane markers, and so on). Conceiving of autonomous vehicles as communication platforms is not just useful for capturing the internal computational operations of these systems; this framing also helps us to understand their fundamental reliance on communication and other outside infrastructures. The automobile's communications with these infrastructures work to "choreograph the relationship between technologies and the people using them" (Holt & Vonderau, 2015, p. 72) and the surrounding environment.

Conclusion

We have argued here that mapping turns out to be central to understanding both the technology and culture of the "Internet of cars." This means we need to adapt and extend our idea of the automobile as a certain kind of communication platform to take into account the vast amount of work that autonomous (and semiautonomous) cars do in processing and generating mapping data, together with all the information gathering, processing, and analysis involved. We must recognize these not as subordinate or ancillary systems, but as essential elements for the control of the vehicle, integrated into their design at a fundamental level.

Applying the communications platform idea to autonomous vehicles not only helps us understand the affordances for vehicle control more clearly; this approach also has significant implications for their governance and political economy more generally—their regulation, business impacts, and relations to the state. Maps will clearly continue to enable the evolution of disruptive commercial services such as ride sharing. Across a range of public policy areas, their combination with autonomous vehicles is also likely to be highly significant. Here we can note a few examples: If autonomous vehicles communicate their location precisely, that enables new options for taxation and public (and private) revenue collection. These include the expanded application of congestion and road-use charges, already seen as possible solutions to the revenue shortfalls that governments must deal with as the use of highly taxed carbon-based fuels declines. In the area of communications policy, the value of the radio frequency spectrum, a public resource, may increase alongside the volume of mobile machine-to-machine (and V2I) data transmission, vindicating the long transition of television services to first digital broadcast and then Internet distribution models. This burgeoning mode of mobile communication is likely also to propel the investments necessary for the construction of new mobile communications infrastructures, including 5G (Miller Landau, 2017). In relation to energy use, the extraordinary demands of intensive data collection and processing on board autonomous vehicles, and in the cloud, may well turn attention to the management of carbon emissions associated with autonomous vehicles, and the necessary mechanisms to offset these. All these issues will require further, future investigation.

When we trace the emergence of autonomous vehicles, struggles over the ownership and control of maps turn out to be a vital part of the story. The point is a familiar one in the broader scholarship of maps: Their longevity and complexity as sources of power is a staple theme in the historiography (Woods 1992, 2010). The digital transformation of mapping introduces further complexities to that history: The technologies and businesses of digital maps emerged slowly and for a long time remained highly specialized domains. However, geodata and mapping applications flourished as basic ingredients in the rapidly expanding mobile Internet, propelling the extraordinary popular diffusion of geographical information over the last decade. Mapping data that were once rare, acquired only at great expense and difficult to manipulate, have now become embedded as an everyday resource, a building block for transformative place-based media and applications of all kinds, from ride sharing to shopping to augmented reality games. As vehicles have acquired more autonomous capabilities, they have also become specialized mapping machines, both with and without direct human involvement. At least to date, however, this has not meant that the value of maps or the technologies around them has diminished. In fact, maps have become increasingly strategically and operationally important—the "seeds of a new system of mobility" (Urry, 2004, p. 33)—for the transport and communications platforms of the near future, and for their governance.

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