Transition Challenges and Business Models for Green City Architecture Integration

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Introduction

The proposed Green Cities Architecture (GCA) for Urban Traffic Management seeks to leverage advances in short-range and wide-area data communications, pollution sensing, and electronic control systems in vehicles in order to reduce traffic congestion and pollution. Achieving these goals will require changes in the transportation system: primarily changes to vehicles, roadway infrastructure, and traffic signals, but also changes in driver preferences and individual travel behavior. This paper outlines the goals of GCA, the changes that will be needed to achieve those goals, and the regulatory and business pathways to achieve those changes.

Vehicle Advancements Needed to Support GCA Goals

GCA Goal 1: Reduce Traffic Congestion

In this section, we discuss the potential of the GCA architecture to optimize traffic flows at various scales. Traffic optimization can occur on individual roadway links (roadway segments), groups of links or segments (corridors), and at nodes (intersections). In general, optimization is meant to ensure that the traffic system operates efficiently, without delay imposed by demand in excess of capacity or inefficient traffic controls.

Let us consider three levels of optimization, herein referred to as macro, meso, and micro. Macro-scale optimization applies to regional trips, typically greater than five miles in length. It balances demand *between* high-capacity roadways (interstates, highways, and expressways) and *among* groups of medium-capacity roadways (arterials and collectors). Meso-scale optimization involves localized balancing of roadway links based on current and anticipated demand: for example moving traffic between parallel arterials and collectors. Micro-scale optimization involves smoothing of traffic flows on individual roadway segments (“links”) via the regulation of speeds, as well as adjusting signal timing at intersections (nodes) to smooth traffic and reduce aggregate travel times. Other research within this project offers an in-depth look at network optimization techniques at various scales in greater detail.

Vehicles and infrastructure must adopt several GCA functions in order to enable all levels of traffic optimization. Connection to a central server enables macro-scale optimization and possibly meso-scale optimization. Connection to distributed traffic signal access points enables vehicle-to-infrastructure communication and meso- and micro-scale traffic optimization, as well as reporting of data from in-vehicle sensors. These functions are described in

Table 1 below.

Table 1 - Functionalities needed for optimization

Function	Enabled by	Vehicle Reporting	Vehicle Receiving	Enables
Navigation Server participation	Data connection to wide area network	Current location, current velocity, intended destination	Route options, tolling information, traffic conditions and events	Visual or audio communication about voluntary options to optimize macro-scale and meso-scale network efficiency
Connection to Traffic Signal Access Points	Data connection to traffic signal access points	Current acceleration, RPM, and other engine conditions	Traffic signal information (e.g. seconds to green or yellow); transmission of instructions for Micro-scale link and node optimization;	Visual or audio communication about voluntary options to optimize micro-scale link and node efficiency
Integration with in-vehicle displays	Navigation server (Class 3A) and traffic signal access point (Class 3B) integration with central vehicle bus	Status of other vehicle systems not connected to On-Board Diagnostic (OBD)	Instructions for vehicle systems not connected to (OBD)	Use of in-vehicle displays to communicate voluntary optimization options
Integration with in-vehicle control systems	Connection to central vehicle bus in NHTSA Level 1 or higher vehicle automation	Control state of vehicle systems (automated or human)	Instructions for on-vehicle actuators (e.g. adaptive cruise control)	Communication to vehicle of micro-scale link and node optimization; with system control of compliance

Many of the barriers involved in introducing GCA for urban traffic management involve transitional and phasing challenges. The transitional challenges involved in introducing new vehicles capable of GCA functionality and retrofitting GCA functionality into existing vehicles are covered later in this paper. The core adoption challenge is to incorporate data communications capabilities within vehicles, i.e. making them connected.

Table 2 outlines two vehicle connectivity attributes and the functionalities they enable.

Table 2 - Connected vehicle attributes and functionalities

Attribute	Safety Functionality	GCA Functionality
Dedicated Short-Range Communications (DSRC)	• V2V and V2I communications • Warnings of out-of-view vehicles and incidents • Warning of adverse roadway conditions (real-time, from nearby vehicles)	• Enables communication with traffic signal • Enables "green wave"
Mobile Network Data Communications	• Warning of adverse roadway conditions (delayed, from central server)	• Enables communication with and participation in Navigation Server • Wide Area Network connection

DSRC will be introduced into new vehicles primarily due to safety benefits. Mobile Network Data Communications has been integrated into existing vehicle systems because of real-time information and navigation benefits, a feature of the Green City Architecture. Mobile Network Data Communications can be integrated into vehicles via smartphones or dedicated in-vehicle devices.

GCA Goal 2: Environmental Benefits

The Green City Architecture will allow researchers and emissions analysts to understand harmful pollutants at higher spatial and temporal resolutions than has previously been possible. The GCA system will also increase the coverage of real-time pollution sensors needed to identify spikes in air pollution. The combination of better modeling and increased measurement will enable more precise air quality warnings and exposure mitigation.

Realizing the environmental benefits of the GCA requires at least some vehicles to sense and report information. A vehicle's emissions depend on three factors: the fuel consumption rate, the air/fuel ratio, and the emissions control system. In the past, without the aid of on-board sensing equipment, emissions modelers estimated the fuel consumption rate and vehicle power based on speed and acceleration, and generally assumed constants for the air/fuel ratio and for the emissions control system by vehicle class and model year. Under the GCA, many of these parameters could be measured directly from the vehicle, rather than calculated or inferred based on extravehicular sensors.

A vehicle's on-board sensing capability can be classified into four tiers, outlined in **Table 3** below. Higher tiers produce greater environmental-related benefits for the GCA system.

Table 3 - GCA emissions sensing tiers

Tier	Description of Real-time Vehicle Data Available
Tier 1	GPS-based position (latitude & longitude), acceleration (gravitational forces) via non-integrated device
Tier 2	Tier 1 plus engine status (RPM, fuel use and composition, on-vehicle sensor readings that can be used in pollution modeling) via a non-integrated device
Tier 3	Tier 2 via a vehicle-integrated device
Tier 4	Tier 3 plus mobile sensing of air pollution

Tier 1 vehicles can calculate vehicle speed using an on-board smartphone or other non-integrated device with a GPS receiver and an accelerometer. However, the drawback of a non-integrated device is that it may also sense non-vehicular motion, which can reduce the reliability of reported data; for example if the device falls to the floor, it would report high gravitational forces on the z axis. In Tier 1, fine-scale vehicle emissions modeling would be based on assumptions or reported information about vehicle class and age. A vehicle’s modal profile or engine load can be inferred based on current speed and gravitational forces (longitudinal and latitudinal acceleration).

Vehicles in Tier 2 would use a non-integrated device to directly report parameters such as speed, engine load, air/fuel ratio, and capabilities and current status of the emissions control system. Tier 3 vehicles accomplish the same tasks as in Tier 2, but via a device integrated within the vehicle. Fine-scale vehicle emissions modeling would be based on actual data, either reported in real-time or delayed. Finally, Tier 4 enables the direct measurement of ambient air pollution, which would be useful in validating and improving the emissions models based on data reported from Tier 1 – 3 vehicles.

Vehicles with on-board sensing equipment and data connection to the wide area network or infrastructure can contribute sensed information to the GCA system, either in via DSRC or the Mobile Network Data Communications.

GCA Classes and NHTSA Levels: Defining Future Vehicles

We define six GCA vehicle classes in order to depict the possible range of GCA capabilities within vehicles. Later in this paper, we refer to vehicles by class in describing possible transition challenges.

Table 4 - Combined GCA environmental and congestion capabilities: Defining GCA vehicle classes

GCA Vehicle Class	Description	GCA Functionality
GCA Class 0	No connection to GCA System	None
GCA Class 1	Connection to GCA System with non-dedicated device not connected to vehicle (e.g. smartphone only)	• Tier 1 on-vehicle sensing • Navigation Server Participation
GCA Class 2	Connection to GCA System with vehicle-connected non-dedicated device (e.g. smartphone with connection to OBD-II, possible with 1996 and later vehicles initially sold in US)	• Tier 2 on-vehicle sensing • Navigation Server Participation
GCA Class 3A	Dedicated in-vehicle device, connected to vehicle systems via central vehicle bus (not OBD-II)	• Tier 3 on-vehicle sensing • Navigation Server Participation • Integration with in-vehicle displays and systems
GCA Class 3B	Dedicated in-vehicle device with DSRC capability, connected to vehicle systems via vehicle bus other than OBD-II	• Tier 3 on-vehicle sensing • Navigation Server Participation • Integration with in-vehicle displays and systems • Connection to Traffic Signal Access Points
GCA Class 4	Dedicated in-vehicle device with DSRC capability, connected to vehicle systems via vehicle bus other than OBD-II. Connection to on-board systems designed to measure ambient air pollution.	• Tier 4 on-vehicle sensing • Navigation Server Participation • Integration with in-vehicle displays and systems • Connection to Traffic Signal Access Points

GCA Class 1 vehicles have no integrated GCA functionalities, but limited GCA functionality is possible through the use of a mobile device with a GPS receiver, accelerometer, and network connection. A GCA Class 1 vehicle can report its location and receive routing information. A GCA Class 2 vehicle builds off of Class 1 capabilities with integrated GCA functionalities that can help improve vehicle emissions modeling. A GCA Class 2 vehicle may collect vehicle operations data (RPMs, sensor data) and report information that classifies whether a vehicle may produce less, about the same, or more emissions than expected by a model which uses vehicle class and age to distinguish emissions factors.

When GCA Class 3A, 3B and 4 vehicles also possess automation capabilities rated at NHTSA level 1 or higher (e.g. adaptive cruise control), these vehicles can incorporate feedback from traffic signal access point into cruise control to smooth traffic flow and form platoons that ride the "green wave" to improve vehicle fuel economy. The "green wave" concept is covered in other areas of this research project and describes the synchronization of traffic signals to minimize acceleration and deceleration vehicle cycles; which improves traffic flow and reduces fuel use.

GCA Class 4 vehicles have on-vehicle sensing capabilities, a feature useful in collecting air quality measurements and calibrating and validating emissions models.

NHTSA Automation Levels

The National Highway Transportation Safety Administration (NHTSA) is developing policy related to automated vehicles. The NHTSA has defined five levels of vehicle automation, which are summarized below. Some vehicle automation functions combine with vehicle connectivity to provide GCA functionality.

Table 5 - NHTSA automation levels

NHTSA Level	Vehicle Control
Level 0	Driver is in complete and sole control
Level 1 - function-specific automation	Vehicle systems are in control of one or more specific functions, such as electronic stability control or adaptive cruise control. Driver controls all other functions
Level 2 - combined function automation	Vehicle systems are in control of at least two primary control functions.
Level 3 - limited self-driving automation	Vehicle systems can fully control all safety-critical functions during some portion of the driving task; driver has ceded control
Level 4 - full self-driving automation	Vehicle systems take full control of all functions for an entire trip

Source: (National Highway Traffic Safety Administration, 2013)

Vehicle Phasing and Adoption

GCA Class 1 capabilities, which require a smartphone or other connected device, are possible without any modification to the vehicle. GCA Class 2 vehicles may be introduced through new vehicle designs or simple installation of aftermarket devices to OBD-II connectors on existing vehicles. Adoption of GCA Class 3 and higher vehicles requires the introduction of integrated, dedicated equipment, either at the factory or via a professional retrofit. As such, the introduction of vehicles with GCA Class 3 or higher capabilities will be limited by vehicle turnover in the marketplace, and the perceived benefits of the system amidst evolving competition for vehicle retrofits.

Vehicle Turnover in the United States

Data on vehicle turnover and age distribution provide insight into the potential GCA adoption cycle. A federal mandate to require all vehicles to have GCA Class 3 or higher capabilities would be expected to have effects in line with historic adoption patterns, with some adjustments for macroeconomic conditions and increased survival rates for new models. Based on historical data, shown below in Table 6, at least eight years would pass between the first model year of the mandate and the point when half of all vehicles on the roads had GCA Class 3 or higher capabilities.

Table 6 - Distribution of motor vehicle ages - nationwide

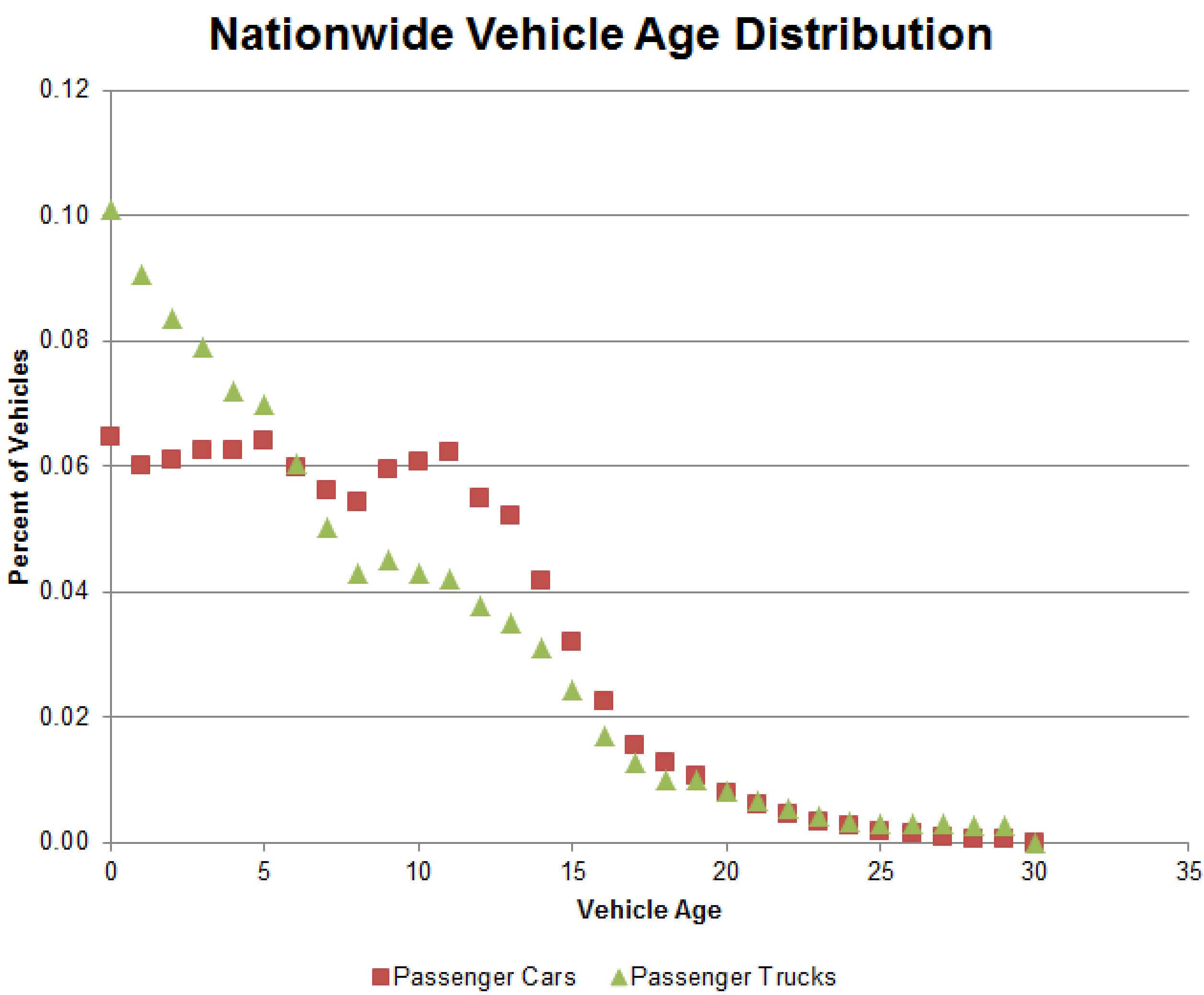
Age	Percent of passenger cars newer than age
5	31.1%
10	60.5%
15	87.7%
20	97.0%
25	99.5%

Source: (U.S. Environmental Protection Agency, 2010)

Vehicle Age Distribution

Figure 1 below shows the long tail of vehicle age distribution. Vehicles sold prior to any federal mandate would survive long into the future, some over 20 years. The relative frequency of older vehicles should inform implementation scenarios that have minimum thresholds for GCA-capable vehicle saturation, such as some pathway for aftermarket integration into existing vehicles.

Figure 1 - National vehicle age distribution



Source: (U.S. Environmental Protection Agency, 2010)

Table 7 - Median vehicle age in urban versus non-urban areas

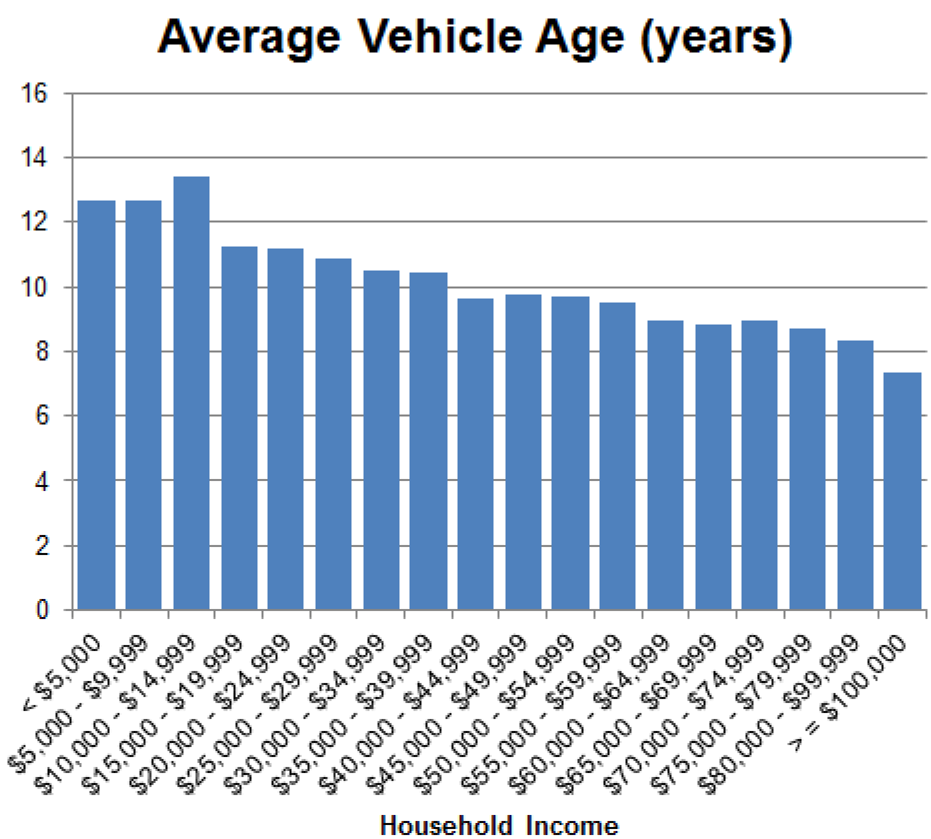
	Average Vehicle Age (Mean)	**95% confidence interval**
Nationwide	9.39	
In Urban Area	8.95	.1289
Not in Urban Area	10.14	.2165

Source: (U.S. Federal Highway Administration, 2011)

Those in urban areas may be quicker to adopt vehicles with integrated GCA capabilities as the average vehicle age is lower in those areas. Additionally, the congestion-reduction benefits of GCA functionality will have more value in areas with traffic congestion, often urban areas.

It's also likely that those with less income will be slower to adopt vehicles with integrated GCA capabilities. Average vehicle age is negatively correlated with household income. The equity implications of a transition to automated or connected vehicles should be addressed in future research.

Figure 2 - Vehicle age and income distribution



Source: (U.S. Federal Highway Administration, 2011)

Adoption Thresholds Needed to Produce Public Benefits

In order to justify public subsidy in GCA infrastructure, the system may need to create benefits non-users as well as users. Even low saturations of GCA Class 4 vehicles can greatly improve real-time emissions measurements, and implementing these capabilities on publicly-owned fleet vehicles and transit buses can greatly improve measurements. Better information about the spatial and temporal variability of vehicle and non-vehicle pollution can also benefit the public. This information can be used to identify gross polluting vehicles and to build roadway infrastructure and near-roadway structures to minimize pollution exposure. Relatively small saturations of vehicles with GCA Class 2 and above capabilities that report data useful for emissions modeling may also provide public benefits. The GCA system can also benefit non-users by optimizing the flow of the roadway network at macro-, meso-, and micro-scales.

Macro-Scale Traffic Flow Optimization

A key feature of the Green Cities Architecture is the Navigation Server, which will provide traffic information and route options to vehicles making long-distance trips. The Navigation Server must achieve two participation thresholds in order to measurably optimize macro-scale travel:

- A minimum adoption level is needed to provide sufficient real-time information about the transportation network for use in optimization. This information can be collected from vehicles or from infrastructure. Greater coverage of connected infrastructure-based sensors reduces the onus on vehicle adoption.

- A minimum compliance level is needed in order to reduce traffic delay for non-users. Some users must adjust their routes in order to improve traffic flow over the status quo.

A user receiving high-quality traffic information with responsive route suggestions benefits from this information, regardless of the adoption threshold. The user will adjust his route, departure time, or other aspects of trip-making in order to reduce his exposure to delay from traffic congestion. The potential reduction in delay would be greater during congested times, which offers an opportunity for initial targeting of GCA's Navigation Server capabilities. An additional user benefit is greater travel time reliability, which reduces the buffer a punctual driver must add to anticipated trip times due to the daily variability of travel times on a given route.

Travel time benefits to those without GCA-capable vehicles occur when all vehicles experience travel time savings due to GCA optimization. This occurs at some compliance threshold, *n*.

Estimate of *n*: vehicle flow benefits come at 20% penetration of variable speed limit/ speed harmonization (automated) (Cooperative Vehicle Highway Systems to Improve Speed Harmonization)

A more precise range for the compliance threshold should be identified by future research.

Meso-Scale Traffic Optimization

Realizing traffic optimization benefits at the meso-scale is a key threshold for GCA, as 76.2% of all vehicle trips made by households in urbanized areas are less than 10 miles in length (NHTS, 2009). Under the GCA system, meso-scale optimization balances vehicles among parallel routes. Within the GCA proposal, local connected infrastructure rather than the central

Navigation Server provides this functionality. Thus, GCA requires a minimum infrastructure deployment threshold for infrastructure in order to realize meso-scale optimization benefits. Some meso-scale optimization may be possible using the Navigation Server architecture, or third-party applications that provide similar functionality while bypassing the GCA system. Such a strategy may be part of a viable plan to introduce GCA-capable vehicles and infrastructure, as the DSRC requirement (GCA Class 3B and above) is a significant barrier to achieving GCA benefits for shorter trips. Meso-scale optimization can also help in creating dynamic complete networks, with a range of routes offering automobile-priority, transit-priority, and bicycle-priority, helping produce a greater level of public benefits to justify expenditures in GCA infrastructure.

Micro-Scale Traffic Optimization

Micro-scale traffic optimization requires GCA Level 3B and 4 vehicles with integration to partially or fully-automated vehicle systems. Such vehicles can adjust their speed automatically, through use of adaptive cruise control that harmonizes speed with other vehicles. The infrastructure needs to be connected and responsive to allow for adaptive traffic control devices, such as traffic signals, dynamic lanes, and variable speed limits. This puts the onus on government to fund and deploy GCA infrastructure for those Level 3B and 4 vehicles to achieve benefits.

Future research is needed to study the saturation threshold of GCA Level 3 and 4 vehicles required to induce speed harmonization among noncompliant vehicles, in order to produce the "green-wave" phenomenon in which responsive traffic signals optimize the flow of a platoon of speed-harmonized vehicles. Initially, planners may seek to prioritize GCA infrastructure deployment on congested routes in urban areas where dynamic lane restrictions can increase the speed of transit vehicles, providing a public benefit. Initially implementing GCA on highly-utilized urban corridors can create additional incentives for those who use the corridors to acquire GCA capabilities in their vehicle, or seek out new, GCA Class 3B vehicles. Future research can also study prioritization options for minimum thresholds of GCA infrastructure required for micro-scale optimization.

Limitations of Voluntary Adoption for GCA Vehicles

Voluntary adoption of GCA capabilities is one pathway for automobile manufacturers to produce and consumers to demand GCA-capable vehicle. Under this pathway, vehicle manufacturers would voluntarily integrate GCA Level 3 and higher capabilities into some new vehicles. Vehicle owners would retrofit their vehicles or use non-integrated devices. Under voluntary adoption, these changes would occur when manufactures and users perceived some benefit from access to the GCA system. Vehicle manufacturers and owners would consider the merits of GCA against an evolving competition of GCA-like services.

Evolving Competition

The GCA System will need to compete with an evolving baseline of vehicle and app capabilities that provide driver information and congestion avoidance without a requirement for DSRC or V2X communications.

Many advances in in-vehicle automation and on-board sensors can progress independently of vehicle connectivity, enabling the same or similar level of GCA-enabled functionality. For instance, on-board remote-sensing technology can sense the presence of nearby vehicles, and when combined with partial automation, vehicles can adjust control systems accordingly. Already, adaptive cruise control and blind spot warning systems are advancing without the need for data connectivity and broadcasts between vehicles.

Similarly, advances in mobile and cloud computing may make certain GCA functionalities redundant. Applications like Waze and Google Maps deliver traffic conditions and incident data that are relevant to relevant to macro and meso-scale route optimization. These applications used crowd-sourced data – speed, position, and user reports – to infer and report roadway conditions to other users. Many consumers maintain smartphones or other mobile devices for non-navigational purposes, and in some areas, these applications have achieved saturation levels required to provide sufficient coverage of real-time traffic information. Mobile devices do not require vehicle integration to sense or deliver traffic information, but future integration between mobile devices and vehicle systems could streamline information delivery from applications to drivers, further reducing the added value of the GCA system.

Continued advancements in on-vehicle sensing, automation, and mobile device connectivity will narrow the range of expected benefits that a V2X and GCA implementation can provide, changing the manufacturer and consumer's cost/benefit analysis over time. Under a voluntary adoption scenario, some elements of the GCA system may fall victim to a late-mover's disadvantage.

Recommended GCA Implementation

The Green City Architecture will be capable of collecting a rich and diverse set of data with a broad array of applications for government agencies. However, experience suggests that the public is sensitive to privacy concerns, and if the project is to gain public acceptance, motorists must be offered a choice of whether to "opt in" to sharing data. The literature suggests that convincing motorists to opt in will require incentives, monetary or otherwise, as well as assurances with regard to the handling and use of the data collected.

We consider two basic approaches agencies can use to gain access to motorists' GCA-based data: i) offer value-added services through private firms, and ii) institute a VMT fee. We ultimately recommend that agencies adopt both approaches simultaneously, while taking steps to safeguard user privacy. In addition, we recommend phasing in the vehicle hardware for GCA through a factory installation mandate, supplemented by voluntary rather than mandatory retrofits. As much as possible, GCA should leverage other systems installed in vehicles and focus on providing the connectivity function, which will be the core contribution of the system.

The value-added service approach

In the value-added service approach, private firms can offer a selection of services, such as pay-as-you-drive auto insurance, automated payment of parking fees, or automated payment of tolls. The firms would require access to GCA data in order provide these services, and motorists would be required to opt in as a condition of receiving the services. Agencies would act as an intermediary, by collecting data transmitted from that motorist's vehicle and sharing it with, or perhaps selling it to, the service providers. The service providers would earn revenue through subscription fees they charge their users.

For example, the success of General Motor's OnStar business unit demonstrates that there is a market for the types of services private firms could provide using GCA data. OnStar is a two-way communication system, developed by GM in the 1990s, and it is capable of a variety of services, including navigation, vehicle diagnostics, stolen vehicle assistance, emergency assistance, and mileage-based insurance. The system is typically factory-installed, and GM offers it to vehicle owners on a subscription basis, with a free trial period for new vehicles. GM states that OnStar is profitable, with 6.4 million subscribers worldwide and a renewal rate of over 60 percent.

Similar to the GCA model, OnStar requires users to relinquish personal data in exchange for value-added services. OnStar's privacy policy allows GM the right to sell user data to third parties, though only in anonymized form. As of 2011, GM claims it has not exercised this right, but the fact that it could do so at any time does not appear to be a major constraint on its business (Eisenstein, 2011). In the case of GCA, however, motorists must be comfortable allowing local governments to act as an intermediary and view and perhaps even sell the data. With a government agency as the third party, motorists might perceive GCA as a significantly greater privacy threat than OnStar. Sorensen (2010) argues that the public is warier of sharing personal data with the government than with private firms, such as credit card companies and cellular service providers. If a GCA-like system were to become mandatory for all vehicles, motorists might feel that they are being coerced into sharing data.

On the other hand, public acceptance of sharing data with private firms might have more to do with the value of the services provided by the firms than with the fact that the firms are private. Public acceptance of data sharing associated with GCA may depend more on the attractiveness of the value-added services available than on how the data is handled and who has access to it. The perceived attractiveness of the technology as a whole will likely depend on how agencies manage the public relations aspect of their programs. Agencies will need to convey to potential users the personal benefits they can derive from the technology. Iachello and Hong (2007) argue that Xerox Palo Alto Research Center's (PARC) late-1980s ubiquitous computing system failed to gain public acceptance partly because PARC emphasized the technological ingenuity of the system rather than the system's value to the end user.

It should be noted that different value-added services will require different types and amounts of data to be transmitted, and it is not clear whether users would find it acceptable to share more data than is required to provide the service to which they subscribe. Thus, an opt-in for a single service might not provide agencies with the full array of data available from the motorist's GCA-equipped vehicle.

The VMT fee approach

In the second approach, agencies would use GCA to administer a VMT fee. Motorists who pay these fees would be required to opt in to at least some data sharing, allowing agencies to access at least some of the data collected by the GCA devices.

During the early years of the technology, a large portion of the fleet would not be equipped with GCA hardware and therefore could not be assessed a GCA-based VMT fee. Agencies could still assess a mandatory fleet-wide VMT fee by requiring odometer readings for non-GCA-equipped vehicles. However, although odometer readings are a relatively inexpensive option, they can be difficult to enforce, vulnerable to fraud, and burdensome to users (Sorenson, 2010).

An alternative strategy would be to offer the GCA-based VMT tax as a substitute for the fuel tax. For example, in two pilot studies by the Oregon Department of Transportation (ODOT), participants paid the VMT fee *in lieu* of the fuel tax. A preliminary finding from ODOT's current study is that the VMT fee can generate at least as much revenue as the fuel tax, dependent upon the amount of the VMT fee and the fleet-wide fuel economy (mpg) (Whitty J. M., 2013). However, to make the offer attractive to motorists on a larger scale, agencies would presumably need to set the VMT fee below what motorists would typically pay in fuel tax. Sorensen (2010) mentions that agencies could raise the fuel tax in order to accommodate a VMT fee that generates adequate revenue while still being attractive to motorists.

The above options allow for a policy of voluntary opt-in, eliminating the need for a costly mandatory retrofit program and providing time for GCA to gradually gain public acceptance. Once GCA achieves public acceptance and widespread deployment, agencies would ideally be able to enforce a mandatory GCA-based VMT fee, ending agencies' dependence on dwindling fuel tax revenues and providing a more reliable source of transportation funding for the long run.

From VMT Fee to Congestion Fee

Agencies could ultimately switch from a VMT fee to a congestion fee. In the case of a congestion fee, the GCA system would automatically set a price for each road segment. The prices would fluctuate in response to real-time traffic conditions. When a segment became congested, the price would rise, discouraging travel on that segment and restoring it to an uncongested state. The on-board unit (OBU) would communicate the prices to the motorist.

While the congestion pricing scheme could assess users a uniform price based on a vehicle's current position and route, with connected vehicles under the GCA system, users could signal their intent to take a certain route at a certain time at some point in advance of their actual trip. This way, the system could more accurately predict the congestion on each segment and provide better information to travelers. Prices could potentially be used to incentivize users to signal their intent – or "reserve a trip" – further in advance.

In addition to reducing congestion, which is a central goal of the GCA project, a congestion fee also introduces new revenue opportunities that could help finance the infrastructure necessary to operate the system. Congestion fees are designed to encourage motorists to shift the time, route, or mode of their trips. There could be value in allowing advertisers to target place-time or place-specific advertisements at motorists who are in the midst of this decision-making process. Certain establishments may be eager to advertise to motorists who, for example, are currently located nearby and who are likely to *remain* nearby for some period of time because they are shifting their trip departure time due to temporarily high congestion prices. The OBU software could use information about the driver's current location and the prices of potential routes to tailor advertisements to the driver.

Despite their benefits, congestion fees would not be an effective way to transition into a GCA system – they would be more appropriate as an eventual goal *after* transitioning to GCA using a VMT fee. First, a VMT fee is technologically far simpler than a congestion fee, and agencies will be equipped to implement it sooner. Second, a congestion fee requires an overwhelming majority of motorists to participate, whereas a VMT fee has no participation threshold. Third, agencies can use a VMT fee to encourage motorists to adopt GCA by setting the fee below what motorists would typically pay in fuel tax; congestion fees are determined by traffic conditions and may not be a better deal for motorists than the fuel tax.

A VMT fee could help pave the way for congestion pricing culturally and politically simply by introducing the idea of road pricing to the public. VMT fees could also help agencies develop experience with road pricing and resolve some of the technical issues that may arise. However, the transition from VMT fees to congestion pricing would still be challenging and complex. Perhaps the greatest challenge would be political acceptability. Congestion pricing would require agencies either to mandate participation or to find a way to entice motorists, including those who have not already voluntarily participated in the VMT fee. Further research will be required to determine how agencies can address these challenges.

A hybrid of value-added services and VMT fees

The value-added services approach and the VMT fee approach are not mutually exclusive, and the optimal model would probably be a hybrid of the two. Some motorists will be enticed by the value-added services offered by private industry, while others will be enticed by the discounts or other incentives offered by agencies. Assuming agencies would like to acquire data from as many vehicles as possible, it would make sense for them adopt an approach that encourages both types of enticement.

Given that the VMT-fee model essentially requires agencies to *purchase* data from users by offering discounts and incentives, while the service-provider model involves acquiring data for free (and perhaps even selling it), agencies should rely on the value-added services model as much as possible and supplement it with the VMT-fee model, adjusting the incentives in the VMT-fee model to obtain the desired amount of data. Agencies would presumably have to offer the same data-sharing incentives to motorists who already share data through value-added services.

Drawbacks to VMT Fees

There are two major drawbacks to the VMT fee business model. First, it requires agencies, rather than private firms, to provide the incentives for opt-in. If agencies set the VMT fee lower than the existing fuel tax, then there is a fiscal cost to providing these incentives; if agencies raise the fuel tax in order to make the VMT fee attractive to motorists, then there may be a political cost. Goodin, Baker, and Taylor (2009) suggest that some motorists may choose to pay the VMT fee simply for the convenience of electronic billing and weekly/monthly billing. This incentive would not require fiscal or political sacrifice, but it may not be enough to win over a substantial share of motorists.

The second drawback is that even if motorists are willing to switch to the VMT fee, it is not clear what type and quantity of data they would be willing to allow agencies to collect. As demonstrated by the first Oregon study, administering even a GPS-based VMT fee does not require governments to collect granular data from vehicles (Whitty J. M., 2007) – and it certainly does not require the collection of most of the data that would be required for agencies to utilize GCA to its fullest potential.

Agencies could require motorists to agree to share various types of additional data as a condition of choosing the VMT fee, but this might require agencies to offer stronger incentives. These incentives might be costly for governments to provide, though the cost would likely be temporary and could perhaps be justified in light of future revenue potential and social benefits associated with large-scale adoption of GCA. Alternatively, agencies could unbundle the VMT fee from the data-sharing and offer incentives for data-sharing itself, but this could be perceived as buying people's personal data, or a tax on privacy.

Privacy issues and strategies

Privacy settings

Users can be offered several degrees of opt-in. At the least restrictive extreme, they can choose to share the full array of data that can be collected and transmitted by the system. At the most restrictive, they can choose to share only the data required to deliver the services to which they subscribe. In order to participate in GCA's navigation server, this may include a vehicles current location and intended route, but not engine load and acceleration data useful for emissions modeling.

Different service providers may also offer different levels of "granularity" in their control over privacy settings (Iachello & Hong, 2007). A coarse approach might offer only two or three possible privacy settings, which is simple to understand but runs the risk of leaving some potentially shareable data untapped. Suppose there are only two types of opt-ins: a restrictive option (less data-sharing) and a non-restrictive option (more data-sharing). If a user's true privacy "threshold" lies somewhere between the two options, then the user would probably choose the more restrictive option in order to remain below the threshold, and the agency would lose out on some of the data the user would have been willing to share.

A granular approach would address this issue by offering a large number of privacy settings, allowing users to select precisely which types of data they want to share. If each user could choose precisely the amount and type of data she was willing to share, then agencies would maximize their data intake. However, granular approaches have often proven confusing to users, especially when users are not yet familiar with the service or technology.

Another related consideration is when to prompt users to select their settings (Iachello & Hong, 2007). If the user is prompted when she first begins using the product, she may not have enough information or experience with the product to make an informed decision. One solution is to adopt an "interactive style," in which the system prompts the user at certain key moments when they acquire enough information to make an educated decision. However, this approach might be difficult to implement for GCA services, since users would likely be required to make these privacy decisions while driving, which could raise concerns about unsafe distractions. Moreover, users do not necessarily have a precise or coherent notion of their own privacy preferences or “thresholds”; stated preference often differs from revealed preference (Iachello & Hong, 2007).

It might be acceptable to program the device to share certain types of data by default, while still preserving the option of “opting out.” For many products, such as caller ID and shared calendars, default settings take on great importance because users tend not to change them (Iachello & Hong, 2007). However, it is unclear whether GCA users will exhibit similar behavior, and additional research is required in order to determine what types of data would be acceptable for the devices to share by default.

In principle, agencies could adopt a policy that sets a minimum level of opt-in, requiring that in order to receive any value-added service or to participate in the VMT fee program, users must agree to share a certain pre-defined set of data items. It is difficult to determine what the public’s privacy threshold will be, but it will likely depend on several factors, including the subjective value of the service, the effectiveness of the agency’s public relations, and the public’s evolving views on privacy.

Privacy and the OBU

One privacy issue is how much data the OBU will transmit outside the vehicle and how much data it will store locally. An OBU that transmits all information to a central control is sometimes referred to as a “thin client” approach. In contrast, a “thick client” approach has an OBU that stores more information on-board and only transmits the data needed to calculate fees and charges. De Palma and Lindsey (2011) review several tradeoffs involved in selecting between these two approaches. Thick client systems offer greater reliability, due to their decentralized nature; malfunctions only affect a single vehicle, rather than the entire network. Thick client systems offer more privacy, since detailed travel information does not leave the vehicle, but also less flexibility, since changes to the network would have to be uploaded to each individual OBU. Additionally, the OBUs have to be much more sophisticated, with a greater memory capacity. While thick client systems are generally associated with greater privacy protection, de Palma and Lindsey (2011) note that there could still be concern over whether data stored on the OBUs could be used by insurance companies to adjust rates or in court to establish fault in an accident.

In practice, there are many intermediate approaches along the thick-client/thin-client spectrum, each striking its own balance with respect to the tradeoffs mentioned above. It may be possible to design the GCA system in such a way that it can accommodate a range of intermediate approaches, allowing each user to select his or her preferred approach, depending on the user’s level of privacy concern, preferred method of payment for VMT/congestion fees, desired set of value-added services, and so forth.

The 2007 ODOT study tested a mileage-based user fee system using a thick-client approach. The per-mile rate varied depending on the time of day and the geographical “zone,” and the OBU collected locational information via GPS in order to determine how many miles the user traveled in each zone[1]. The OBU did not transmit the actual GPS data – it only transmitted the number of miles traveled in each zone. Nonetheless, the use of GPS raised privacy concerns in Oregon, and ODOT cites these concerns as one reason why the concept has not been implemented on a larger scale. In response to the concerns, ODOT is offering non-GPS payment options in their follow-up pilot study. Moreover, the payment options that do involve GPS are managed by private companies so that ODOT can never access specific locational data. Preliminary results show that acceptance of the system among participants is high, and participants feel their privacy is protected. Participants reported that having several payment options made them more comfortable with the program as a whole.

An additional possibility ODOT is exploring in its current study is to allow the motorist to temporarily disable the locational function on their device. The user is simply charged the Oregon zone rate for miles driven while the locational function is disabled. If disabling were to be allowed in a fully implemented program, users might be charged a premium for miles driven while the locational function is disabled, so as to discourage users from strategically disabling the device in high-rate zones.

It is also worth noting that for VMT or congestion fees, agencies will likely face a tradeoff between privacy and auditability (de Palma & Lindsey, 2011; Sorenson, 2010). It may be possible for agencies to administer these fees while collecting only minimal amounts of information, by having OBUs collect the data and compute the fees themselves, but this would limit agencies' ability to respond to motorists who wish to dispute a fee. However, Sorensen (2010) suggests that the OBU could be designed to allow users to download detailed information on the fee calculations.

Data-handling

There are several data-handling strategies that could provide greater assurance to users with regard to privacy protection. One strategy would be for agencies to collect data through a third party responsible for anonymizing the data in such a way that it would be impossible for the agency to link specific data with an individual motorist. This third party could go a step further by eliminating any information that could potentially identify an individual, such as the precise origins and destinations of trips. This strategy could deprive agencies of potentially valuable data, but it still might be a sensible tradeoff in terms of public acceptance.

Case Study: The Event Data Recorder

Recent experience offers some evidence that at least some types of data could be collected without an opt-in. Nearly every new light-duty vehicle now includes a factory-installed Event Data Recorder (EDR), which records "technical information about the status and operation of vehicle systems for a very brief period of time (i.e., a few seconds) and in very limited circumstances (immediately before and during a crash), primarily for the purpose of post-crash assessment of vehicle safety system performance" (National Highway Traffic Safety Administration, 2012). Special equipment is required to retrieve the data.

NHTSA issued standards for EDRs in 2006 that enumerated a set of data items that all EDRs are now required to capture, including:

- Speed vehicle was traveling
- Percentage of engine throttle, percentage full (how far the accelerator pedal was pressed)
- Whether or not brake was applied

Although NHTSA did not issue a mandate at the time, it estimates that approximately 96 percent of model year 2013 vehicles are equipped with an EDR conforming to NHTSA standards. In 2012, NHTSA followed up on its 2006 regulations, issuing a Notice of Proposed Rulemaking for an EDR mandate that would take effect in 2014.

Vehicle manufacturers are required to include a statement in the owner's manual disclosing that the device is implanted in the vehicle – the required statement is printed word-for-word in the 2006 NHTSA regulations. However, vehicle manufacturers are not required to offer motorists the option of opting out. Congressman Capuano of Massachusetts has proposed legislation that would require manufacturers to offer owners an opt-out, but the idea has continually failed to gain traction (Meredith, 2013).

The proliferation of the EDR has gone largely unnoticed by the public, which might suggest that this model would be adequate, at least for certain limited applications. It will be worth considering whether GCA will be able to use a similar privacy model. One might describe this model as "install and disclose" – the manufacturer installs the GCA device in the vehicle and then simply discloses the existence of the device to the vehicle owner, without offering an opt-out.

There are two main concerns with regard to extending this model to GCA. First, there is the question of who owns the data once it is collected. State law currently governs the ownership of data collected by the EDR, and the law differs from state to state. In some states, the vehicle owner is granted ownership of the data and must consent before the data can be released. Some states, however, permit insurance companies to include clauses in their contracts requiring vehicle owners to release EDR data upon request. It is unclear whether there will be federal guidance on this matter.

Second, even if federal law were to deny vehicle owners ownership of EDR data, it is unclear whether this model could be extended to apply to devices capable of transmitting data remotely. EDRs must be accessed physically, using special equipment, in order to collect data stored on them, whereas the GCA devices are designed to transmit data to other vehicles and to infrastructure.

Still, it is important to recognize that the EDR represents a case where the public has evidently accepted a system that collects data related to driving behavior without the provision of an opt-out, and in some states, without explicit legal ownership over the data. Additional research will be required to determine just how far the "install and disclose" model can be extended while remaining within the bounds of public acceptance.

GCA phase-in options

Although the precise costs of GCA devices and infrastructure remain unknown, the literature suggests that a mandatory retrofit strategy would be expensive, technically complex, and unwise from a policy perspective. Before GM began widespread factory installation of OnStar devices, dealer installation was a complex process that cost roughly $1,300 per vehicle (Barabba, Huber, Cooke, Pudar, Smith, & Paich, 2002). A mandatory retrofit for all vehicles in operation would be even more technically challenging because different manufacturers use different technologies and standards (Whitty J. M., 2007). OnStar currently sells an aftermarket device in the form of a rear view mirror for $99, including installation, and it is compatible with almost any vehicle. However, its functionality is limited and its design is simple. Devices for the GCA might be internally-placed and their functionally much more complex. A factory installation mandate for GCA could greatly lower the installation costs by capturing economies of scale.

An additional advantage of a factory-installation mandate is that it gives the technology time to prove itself through voluntary use before programs are implemented that require its use. Iachello and Hong (2007) note that attitudes and behaviors evolve with respect to particular technologies – for instance, early privacy concerns over the landline telephone have now subsided. Typically, technologies experience a sharp rise in privacy concerns during the early stages of product diffusion, followed by a decline as the public becomes more familiar with the technology and begins to perceive its benefits, and as methods are developed to better protect user privacy. A gradual phase-in via factory installation would allow the dynamic processes of product diffusion and public acceptance to unfold concurrently.

One example of a successful factory-installation mandate is On-Board Diagnostics equipment, a technology that monitors emissions control components. The California Air Resources Board first began requiring the equipment for model year (MY) 1991, and the U.S. Environmental Protection Agency mandated a more advanced version of the original equipment beginning with MY1996. The equipment detects malfunctions in the vehicle that could ultimately lead to increased emissions of various pollutants, and it alerts the owner to any problems by illuminating a light on the dashboard. The equipment can communicate with smog check equipment to provide more precise information about the problem. By design, consumers cannot opt out, and tampering with the equipment is a federal offense.

A factory-installation mandate for GCA devices may have consequences for social equity. Lower-income people tend to drive older cars, and they would not see the benefits of GCA as soon as higher-income motorists or those who are purchasing newer vehicles. A retrofit mandate would not necessarily be a more equitable solution either, since it would require all motorists to pay the same amount regardless of income. This concern could be at least partially resolved by providing subsidies for low-income motorists to purchase after-market devices for retrofit so that they may enjoy the benefits of GCA sooner.

Automobile Insurance Pathway

GCA integration through automobile insurance provides one pathway for adoption. Insurers are beginning to introduce devices into policyholders' vehicles in order to assess premiums based on actual miles driven and driving behavior. These second generation on-board diagnostic (OBD-II) connected devices can access mobile network data communications through an integrated radio or a driver's mobile phone.

Because automobile insurance is currently mandated, all vehicle owners or lessees have an existing relationship with at least one insurance company and may be familiar with several others. Insurance is a relatively large vehicle-related expense for household and firms, into which additional expenses needed to support GCA equipment could be absorbed. Alternatively, changes in insurance rate structure resulting from a transition to usage-based insurance could absorb the costs of the transition to the GCA.

Additionally, a well-established marketplace can enhance choice among GCA-providers. A large number of established firms means that firms can compete on both price and other attributes, such as value-added services or privacy protection. Value-added services can address other drivers' needs, such as locating inexpensive gasoline, in addition to accessing GCA navigation services.

There are some drawbacks to using automobile insurance as a pathway for GCA integration into vehicles. Insurance is regulated at the state level, while national adoption would require implementation in all states, districts, and territories. However, because GCA infrastructure can be implemented at a local or regional scale, the adoption timeline between states need not be coordinated. Some states currently prohibit insurers from collecting any additional data other than mileage data, and these regulations would need to be amended in order for insurers to on the role of a GCA service provider.

Under a voluntary adoption scenario, insurers would provide GCA-capable devices to policyholders on request, possibly as part of a usage-based insurance program. Insurers could be required or allowed to decide whether or not to offer GCA-capable devices. To compel all vehicles to become GCA capable, a State Insurance Commissioner would require insurers to integrate GCA-capabilities within their policyholders' vehicles. This would lead to total or near-total saturation of GCA-capable vehicles by a predetermined deadline.

Apps Pathway

While real-time traffic applications such as Google Maps and Waze can create competition for GCA implementation, these applications also create a pathway for GCA adoption. Augmenting crowd-sourced traffic information with data collected from government-owned sensors can enhance the app service's value to users. Smartphone apps would enable GCA Class 1 and 2 vehicles, which do not require dedicated equipment. The combination of Apps and dedicated in-vehicle equipment would enable Class 3 and 4 vehicles.

One benefit of the apps pathway for voluntary adoption is the existing user base. With meso-scale optimization possible at certain saturations of vehicle participation, a built-in user base can enhance the value of the GCA system. More difficult within the apps pathway is compelling users to share their vehicle operations data for use in emissions monitoring or measurement. Government or app providers may grant points or monetary incentives to users who share such data.

Roadway tolling may provide the impetus for large-scale adoption of such apps. Under such a scenario, the apps would query the Navigation Server for current rates, assess route compliance or fees for deviation, and collect tolling fees. The Navigation Server can provide additional value to existing apps users, through use of declared route data to provide apps with enhanced predictive information in addition to estimates of current travel times. The ability to predict the effects of delaying a trip on both travel times and tolls can be a powerful feature of a GCA-connected application.

Building off of Existing Equipment

The incremental cost of GCA equipment could be reduced by "piggybacking" off equipment that is already installed in every new vehicle. In other words, GCA could build off of some of the functionality provided by this existing equipment, rather than duplicating it. The main contribution provided by GCA technology – and the main source of the equipment's cost – would be the V2V and V2I network connections.

The OBD and EDR devices discussed above are two examples of existing equipment that could be leveraged in this way. The OBD is already capable of collecting detailed diagnostics on internal vehicle components. By providing the network connection capability, GCA equipment could, for instance, allow a vehicle to communicate this diagnostics information to other parties, such as manufacturers, that could help the vehicle owner determine the urgency of the problem and select the safest or most cost-effective course of action (Bayless, 2012). Similarly, the EDR is capable of collecting information on whether the brake is being applied at a given instant. With the network connection capability provided by GCA equipment (as well as the locational capability), this information could be used to smooth traffic at a micro level – a braking vehicle could send a signal to upstream vehicles to apply their brakes as well.

In addition to existing systems, USDOT's Research and Innovative Technology Administration is in the process of developing and testing some more advanced systems that could potentially be deployed on a large scale within the timeframe of GCA. These systems all revolve around a network connection capability much like GCA's. However, unlike GCA they have thus far mostly focused on safety rather than environmental objectives. The role of GCA, therefore, would be to leverage these systems to develop applications directly related to environment objectives – most notably, congestion pricing.

Compliance Incentives

The Navigation Server requires some compliance threshold in order for route suggestions to have a real-world optimization effect. A roadway pricing program allows economic incentives for compliance. Under a congestion pricing program, routes and segments would be priced according to their ability to handle additional traffic volume, fully internalizing compliance incentives within the pricing scheme. Under a mileage-based pricing program, vehicles that comply with route suggestions could receive a credit or discount.

Government could also issue credits or discounts for vehicles that report information, with some level of benefits for vehicles that report traffic conditions (coarse information), and a greater level of benefits that report information useful in real-time emissions modeling (fine information).

This strategy would require a pathway for aftermarket installation of GCA-capable equipment (GCA Class 2 or higher) or participation via a non-integrated device (GCA Class 1).

Travel behavior and additional revenue opportunities

A GCA-enabled congestion pricing program could offer some additional revenue opportunities, apart from the toll revenue itself, to help finance the infrastructure necessary to operate the system.

Shifting departure time

Certain merchants may be eager to advertise to motorists who are currently located nearby and are likely to remain nearby for some period of time because of temporarily high congestion prices.

Empirical literature demonstrates that some travelers shift their departure times in response to congestion pricing, though the prevalence of this response varies from site to site, and the magnitude of the shifts varies from individual to individual. The following are some illustrative examples:

- When peak-period pricing was instituted on the San Francisco-Oakland Bay Bridge in 2010, traffic rose by 21 percent in the hour before the morning peak, compared to 3 percent in the hour after (Cervero, 2012)
- An analysis of cordon pricing in Stockholm found that the majority of commuters continued departing within 15 minutes of their original pre-pricing departure time, and 20 to 30 percent reported no shift in departure time at all (Karlström & Franklin, 2009). This study also found that higher-income workers tend to have greater schedule flexibility.
- In Singapore, among morning commuters driving into the priced zone, the percentage departing before the beginning of the priced period increased from 28 to 42 percent after pricing went into effect (Evans, Bhatt, & Turnbull, 2003).
- A survey of travelers on six Port Authority bridges and tunnels connecting New Jersey and New York found that less than one percent of motorists shifted departure time without shifting mode as well in response to peak period pricing. Traveler flexibility was estimated at 20 minutes and 12 minutes for early and late arrivals to work, respectively. This limited flexibility was the most commonly cited reason for not changing travel behavior (Holguín-Veras, Wang, Xu, & Ozbay, 2011).
- In a stated preference survey for a peak period pricing system in the Netherlands, switching to off-peak driving was the most popular alternative to driving during the peak (Tillema, Ben-Elia, Ettema, & Delden, 2013).

- In a survey of travelers on the Tappan Zee Bridge, 72 percent of respondents reported having some degree of flexibility in departure time, though travelers with higher incomes were less flexible, as were schoolteachers and government employees (Adler, Ristau, & Falzarano, 1999).

Survey results from a Dutch pilot program offer a glimpse into some of the underlying behavioral factors involved in time-shifting (Ben-Elia & Ettema, 2011). The program is rewards-based, offering participants cash and other incentives in exchange for avoiding driving during the morning peak period. The survey found that shifting trips to off-peak hours was the most common alternative to driving during the peak. Women were less likely to change their behavior than men, potentially due to stricter time constraints involved in household duties. Participants who had discussed flexible work hours with their employers were more likely to change their behavior. Unsurprisingly, participants demonstrated a high degree of inertia in their behavior; those who made many peak-hour driving trips before the program were less likely to take advantage of the rewards offered by the program. Of those who did change their behavior, 40 percent made alternative arrangements with their employer, and 30 percent made arrangements with their family. Finally, participants who made more frequent use of traffic information were more likely to delay their departure time.

The above observations notwithstanding, the literature does not yet provide a conclusive account of how time-shifting as a response to congestion pricing differs across various segments of the population. Future research could analyze the importance of demographic variables in explaining behavioral responses. However, the literature does suggest that at least some travelers are willing to shift their departure time in response to congestion pricing. Travelers need ways to productively fill the time that shifting opens up on either end of the trip, and they may respond to specially tailored advertisements displayed on the OBU. For instance, an advertisement might offer 15 percent off at a nearby take-out restaurant, and the traveler could spend time picking up dinner for her family before beginning her journey home. Eventually, the OBU could learn that the user likes moderately-priced Mexican food for dinner, and it could search specifically for these establishments during the evening and feature them prominently on the display. It remains to be determined whether advertising would remain effective for time-shifts that become habitual, rather than ad hoc.

Shifting route

Another possible response to congestion pricing is to shift to a less expensive route. The OBU could facilitate this decision by suggesting alternate routes in cases where the congestion fee on the driver's preferred route is high. The OBU could then display advertisements for merchants located along the alternate route, where the user could run an errand she previously intended to run elsewhere. Because the user may be unfamiliar with the alternate route, the user may be unfamiliar with the merchants located along it, thus making that user a suitable target for advertisements.

The empirical literature contains evidence that some travelers do in fact respond to congestion pricing by shifting to a different route. In their review of the literature, Evans and Bhatt (2003) observe that route shift is the predominant behavioral response in cases where free alternatives are available. Although free alternatives might not always be available under a GCA system, there may often be dramatic price differentials that could induce a similar route-shift response. A study in Stuttgart found that 12.5 percent of drivers switched to a cheaper route when charged a premium of US $2.50 for the route they typically took (Evans, Bhatt, & Turnbull, 2003). In Lee County, Florida, 9 percent of travelers who changed their travel behavior in response to a bridge toll did so by changing their route (Evans, Bhatt, & Turnbull, 2003). In Seoul, on the other hand, little spillover congestion was observed on alternative routes after a congestion charge was instituted on two tunnels, suggesting that perhaps little route shifting occurred (Evans, Bhatt, & Turnbull, 2003). Still, in a national US survey on predicted responses to congestion pricing, route shift emerged as one of the two most prevalent responses for work trips, along with departure-time shift (Arentze, Hofman, & Timmermans, 2003). Respondents who were employed full-time, had a working partner, and had good car availability were found to be more likely to shift routes. Route change was also one of the two most common behavioral changes for non-work trips, along with switching to the bicycle.

In summary, the literature provides promising though somewhat mixed evidence regarding route shifting as a behavioral response to congestion pricing. Additional research on the subject could help determine the viability of potential revenue channels for GCA.

Ridesharing and Carpooling

Given the recent emergence of rideshare services such as Uber, Lyft, and Sidecar, it is worth considering how these services could be integrated into GCA. In particular, the OBU could advertise rideshare opportunities facilitated by these services, providing users the opportunity to share the cost of a congestion charge for a given trip by picking up another traveler seeking a ride along the same route around the same time. This type of service could potentially become a revenue opportunity for the agency administering the GCA system. It would require advancements in ridesharing services, as most services currently match travelers only by origin and not by destination. Matching travelers by origin-destination pairs could further democratize ridesharing, opening it up to ordinary non-professional motorists who simply wish to earn a small amount of extra cash by picking up incidental riders on trips they already plan to take. GCA could also integrate ridesharing with the time-shift and route-shift components of the OBU software. The OBU could, for example, calculate and display the toll cost savings a motorist could achieve by departing earlier or by taking a different route in order to accommodate a trip currently being requested by a prospective rider (with whom the driver would split the toll cost).

There is some evidence that travelers carpool in order to share the cost of congestion pricing. In a survey of SR 91 Express Lanes users – performed at a time when HOV3+ vehicles were charged to use the facility – 46 percent of HOV3+ commuters reported sharing commuting costs, and 34 percent reported that sharing costs was their primary reason for carpooling. (Sullivan, 2000). In Arentze’s national survey (2003), carpooling as a response to congestion pricing was found to be positively associated with higher levels of education, having children, and working full-time; it was negatively associated with living in a high-density urban area, being male, and being over the age of 45.

In addition, in some cases travelers have carpooled in order to qualify for HOV exemptions from congestion-priced tolls. When cordon pricing was imposed in Singapore, for instance, carpools of four or more people increased from 8 percent to 19 percent among vehicles traveling into the cordoned area. Moreover, drivers began picking up "casual carpoolers" before entering the cordoned area in order to obtain the toll exemption (Evans, Bhatt, & Turnbull, 2003, pp. 14-10). In Seoul, HOV volumes increased by 146 percent when congestion pricing was introduced with an HOV exemption (Evans, Bhatt, & Turnbull, 2003). Although a GCA system probably would not offer HOV exemptions, carpooling, as well as ridesharing, present opportunities for travelers to save on toll costs.

It is unclear whether this small but encouraging body of evidence on carpooling can be applied to ridesharing as well. Like carpooling, ridesharing offers drivers a way to split toll costs, though it also involves certain inconveniences such as sharing one's vehicles with strangers. It will be worth monitoring the experience of the existing rideshare services as they mature and examining the possible implications for GCA-facilitated ridesharing.

Trip chaining

One potential response to congestion pricing that is not commonly studied in the literature is trip chaining, i.e. reducing toll expenses by stopping at multiple locations on a single journey instead of making multiple two-way trips. The Stuttgart cordon pricing study found that this was a relatively uncommon response (Evans, Bhatt, & Turnbull, 2003), but further research will be necessary to determine whether trip chaining would be a prevalent method of economizing on travel in other contexts and under more systemic forms of pricing. GCA and its associated applications could be valuable tools for motorists trying to find convenient ways to chain trips, and this could present valuable advertising opportunities for certain types of merchants.

Additional travel behavior insights

Social research performed by the UK Department of Transport provides some additional insight into behavioral responses to road pricing (O'Grady, Millington, Bacon, Bullock, Taylor, & Viner, 2010). The study consisted of a literature review, interviews with experts, and focus groups with the general public. Two of the study's conclusions in particular may carry special relevance to GCA.

First, the study found that an individual's response to road pricing depends on that individual's "approach to spending" and "personality," factors that vary greatly between individuals, even at the same income level (310). Given both the complexity involved in predicting traveler responses and the desire to properly target advertisements, there may ultimately be a market for services that use sophisticated algorithms and statistical techniques to "learn" a traveler's habits and behavioral characteristics based on data gathered by the OBU. It is unclear whether governments could directly monetize these services, though governments could benefit to the extent that these services make advertising more effective and boost advertising rates.

Second, the study found that responses to road pricing depend on the traveler's "ability and preparedness to access, understand and process" the price information; and "when people cannot derive an analytical solution, or choose not to, they will resort to a heuristic or will seek to avoid having to make the choice" (306). In a GCA system, it will be difficult if not impossible for any user to "derive an analytical solution," due to the inherent complexity of a system where each road segment is dynamically priced. The user will thus rely heavily on the information displayed by the OBU for each route option. However, comparing the information for each route will itself require analysis by the user – analysis that the user may "seek to avoid."

This suggests that the user may be easily influenced not only by the route information itself, but also by the way the information is *displayed* on the OBU. If this is the case, then the effectiveness of advertisements – the likelihood that the traveler will be open to suggestions involving alternative routes or departure times – will likewise depend heavily on the way the route information is displayed on the OBU. For example, the order in which the route options are listed may be important, and one can envision a scenario where advertisers pay a premium to display a certain route more prominently. The relative prominence of trip duration, distance (or estimated fuel cost), and departure time could also potentially influence a traveler's decisions as well.

Conclusion

There are a great variety of emerging technologies and V2X systems. These developments are concurrent with rapid developments in mobile applications and increasing mobile device ubiquity. All of these make the best pathway for GCA implementation a moving target. Policy shifts in terms of regulatory frameworks and insurance and infrastructure pricing have the potential to dramatically change the landscape as well. Agencies and firms seeking the benefits of GCA optimization at various scales will need to consider all of these factors, as well as travel behavior, adoption rates, privacy concerns, and rates of vehicle and infrastructure turnover.

Bibliography

Adler, T., Ristau, W., & Falzarano, S. (1999). Traveler reactions to congestion pricing concepts for New York's Tappan Zee Bridge. *Transportation Research Record: Journal of the Transportation Research Board, 1659*, 87-96.

Arentze, T., Hofman, F., & Timmermans, H. (2003). Predicting multi-faceted activity-travel adjustment strategies in response to possible congestion pricing scenarios using an internet-based stated adaptation experiment. *TRB 2003 Annual Meeting CD-ROM*. Transportation Research Board.

Barabba, V., Huber, C., Cooke, F., Pudar, N., Smith, J., & Paich, M. (2002). A multimethod approach for creating new business models: The General Motors OnStar project. *Interfaces, 32*(1), 20-34.

Bayless, S. H. (2012). *Trends in Machine-to-Machine Communications.* Retrieved from The Intelligent Transportation Society of America: http://www.itsa.org/knowledgecenter/technologyscan/1302

Ben-Elia, E., & Ettema, D. (2011). Rewarding rush-hour avoidance: A study of commuters' travel behavior. *Transportation Research Part A, 45*(7), 567-582.

Cervero, R. (2012). Traffic impacts of variable pricing on the San Francisco-Oakland Bay Bridge, California. *Transportation Research Record: Journal of the Transportation Research Board, 2218*, 145-152.

de Palma, A., & Lindsey, R. (2011). Traffic congestion pricing methodologies and technologies. *Transportation Research Part C, 19*(6), 1377-1399.

Eisenstein, P. A. (2011, September 28). *GM'S OnStar service raises privacy alarms.* Retrieved from NBC News: http://www.nbcnews.com/id/44690140/ns/business-autos/t/gms-onstar-service-raises-privacy-alarms/

Evans, J. E., Bhatt, K. U., & Turnbull, K. F. (2003). *Traveler response to transportation system changes: Chapter 14 - road value pricing.* Transportation Research Board. Washington, DC: Transit Cooperative Research Program.

Goodin, G., Baker, R. T., & Taylor, L. (2009). *Mileage-Based user fees: Defining a path toward implementation.* The Texas A&M University System, Texas Transportation Institute. Washington, DC: U.S. Department of Transportation Research and Innovative Technology Administration.

Holguín-Veras, J., Wang, Q., Xu, N., & Ozbay, K. (2011). The impacts of time of day pricing on car user behavior: findings from the Port Authority of New York and New Jersey's initiative. *Transportation, 38*(3), 427-443.

Iachello, G., & Hong, J. (2007). End-user privacy in human-computer interaction. *Foundations and Trends in Human–Computer Interaction, 1*(1), 1-137.

Karlström, A., & Franklin, J. P. (2009). Behavioral adjustments and equity effects of congestion pricing: Analysis of morning commutes during the Stockholm Trial. *Transportation Research Part A, 43*(3), 283-296.

National Highway Traffic Safety Administration. (2013, May). *Preliminary Statement of Policy Concerning Automated Vehicles.* Retrieved from http://www.nhtsa.gov/staticfiles/rulemaking/pdf/Automated_Vehicles_Policy.pdf

O'Grady, A., Millington, A., Bacon, J., Bullock, H., Taylor, L., & Viner, K. (2010). Using social research to measure, understand and predict behavioral responses to road pricing in the UK. *International Journal of Sustainable Transportation, 4*(5), 293-312.

Sorenson, P. (2010). *System Trials to Demonstrate Mileage-Based Road Use Charges.* Washington, DC: National Cooperative Highway Research Program.

Sullivan, E. (2000). *Continuation study to evaluate the impacts of the SR 91 value-priced express lanes: Final report.* Sacramento, CA: California Department of Transportation.

Tillema, T., Ben-Elia, E., Ettema, D., & Delden, J. v. (2013). Charging versus rewarding: A comparison of road-pricing and rewarding peak avoidance in the Netherlands. *Transport Policy, 26*, 4-14.

U.S. Environmental Protection Agency. (2010). *MOVES 2010 Highway Vehicle Population and Activity Data.* Washington, DC.

U.S. Federal Highway Administration. (2011). *National Household Travel Survey.* Retrieved April 4, 2013, from http://nhts.ornl.gov