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Mileage-Based User Fees: Defining a Path toward Implementation Phase 2: An Assessment of Technology Issues

Final Report

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16. Abstract

This report reviews technology options for a mileage-based user fee system in the state of Texas. The report was compiled based on input from a diverse range of sources, including a literature review of existing mileage-based user fee technical write-ups, discussion of an internal technology assessment team at the Texas Transportation Institute, interviews with individuals representing key technology stakeholders, and findings from the first annual symposium on mileage-based user fees. The main focus of this report is to assess the range of possible mileage-based user fee system architectures. These architectures are considered at the logical level (i.e., the flow and transformation of information from raw data describing roadway use to an end bill) with the goal of demonstrating how the process flow of each architecture affects its ability to meet key policy objectives. The report also explores issues related to payment, enforcement, the deployment of on-board units in vehicles, and the potential for technology enabling a mileage-based user fee to be a platform for other value-added services. Finally, the report concludes by identifying key policy questions for Texas that must be addressed before pilot programs can be developed.

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Mileage-Based User Fees – A Path toward Implementation

Phase 2: An Assessment of Technology Issues

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Executive Summary

This report is part of a series of reports studying the feasibility of a mileage-based user fee system in Texas. A previous report sponsored by the University Transportation Center for Mobility™ (UTCM) examined the reasons for considering mileage-based fees in Texas and studied the public acceptability of such a system. That report established a framework for an alternative funding system based on public feedback that included both technological criteria and user-fee criteria. A companion report to this one examines institutional issues that might emerge with a switch from the gas tax to a mileage-based user fee.

Clearly defining and prioritizing the policy and program goals of a mileage-based fee system will be crucial in determining the technological and system configurations that will be needed to support the system. This is due to two factors: 1) the complexity of program and policy goals will necessarily require the development and deployment of more complex technology options; and 2) many policy objectives may conflict with one another. Three aspects of a potential mileage-based user fee system will be affected by policy goals:

- **Roadway use assessment**: the collection of raw data describing vehicular movement.
- **Charge computation**: the data processing by which raw data are used to assess an amount owed.
- **Vehicle-to-back-office communication**: the data transmission by which information used to compute an amount owed or the already-computed amount owed is sent from the vehicle to a back office.

This report provides a discussion on the various policy directives that may influence the above references system aspects and provides examples of logical architectures that may be developed to meet these policy objectives. This report was developed from a unique mix of sources. An inventory of existing and proposed road user fee pilots and programs, both in the U.S. and in Europe, served as an invaluable introduction to the range of technology options. Discussion emerging from the meetings of a technology assessment team represented a valuable source of ideas. A series of interviews with technology stakeholders from the computer software and hardware industry, tolling industry, telecommunications industry, academia, and a state Department of Transportation (DOT) constituted another set of perspectives. Finally, findings from the first national Symposium on Mileage-Based User Fees, which convened in Austin, Texas, on April 14-15, 2009, contributed greatly to this report.

Introduction: The Role of Technology

It is important to situate the discussion of technology options within the larger discussion of design and transition to a mileage-based user fee. Figure 1 illustrates an ideal system design decision-making hierarchy, wherein all discussion of technology should proceed from clearly defined policy objectives. Concrete policy objectives should guide the definition of the system's logical architecture, or the desired flow and transformation of information. Definition of the logical architecture in turn enables the selection of one or more physical architectures, or the specific technologies selected to provide the desired information pathway.

Because the policy objectives motivating consideration of a mileage-based user fee system remain open-ended in Texas, this report is largely concerned with logical architecture options. The logical architecture of a mileage-based user fee system must convert raw data describing vehicle movement to an end bill that is paid by road users. Many of the factors that will determine the public acceptability of a mileage-based user fee system hinge on the logical architecture. System privacy, the ability of users to audit charges they are assessed (to ensure fairness and accuracy), data security, and the various value-added services that can be provided are all logical architecture-level considerations. Thus, while this report does not discuss the full range of technology decisions, it does discuss those technology decisions that are likely to be the toughest to make.

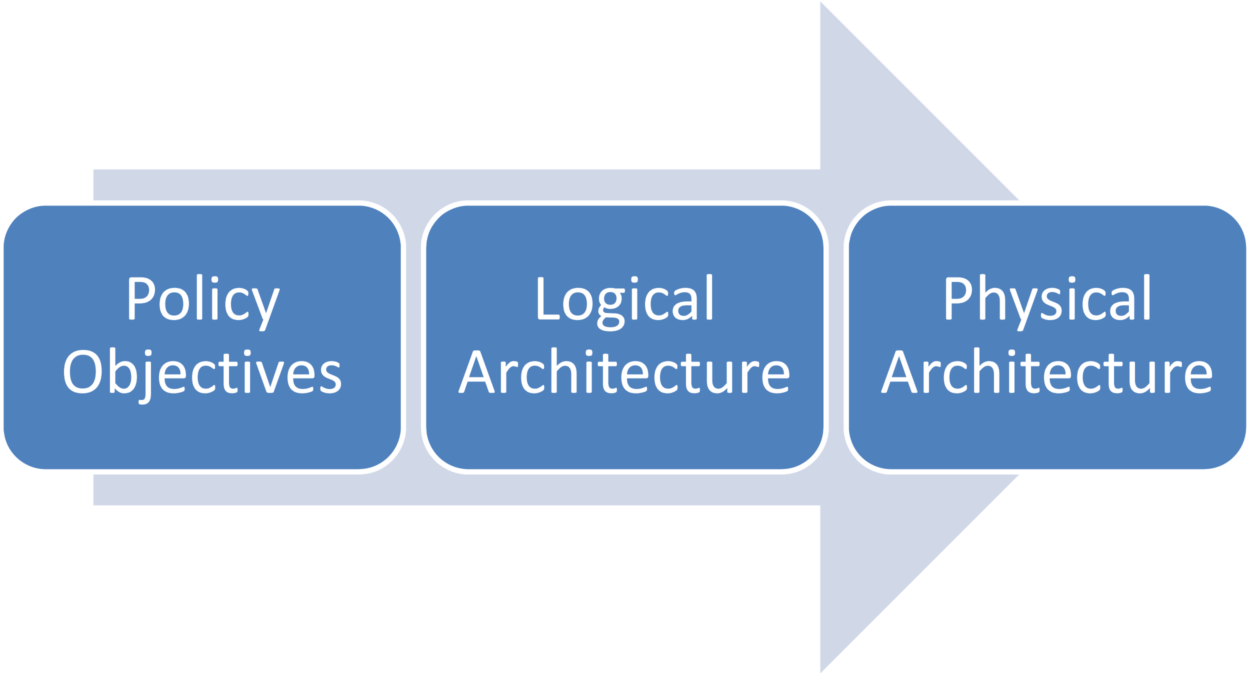

Figure 1: Mileage-Based User Fee System Design Decision-Making Hierarchy

Table 1 below illustrates the wide range of policy objectives that a mileage-based user fee system could be designed to achieve. There are two crucial reasons why definition and prioritization of policy objectives should be the highest level of decision making. First, clear policy objectives are needed to determine the level of technological sophistication required. A more technologically sophisticated system can support more policy objectives but could also lead to higher system costs, added maintenance needs, more points of failure, greater consequences of failure, and potentially more avenues for abuse. For instance, if a mileage-based user fee is pursued merely to address the erosion of fuel tax revenues, a system could be implemented using annual odometer readings. This system would, however, potentially result in an unfair assessment of charges, as motorists would be assessed a fee for mileage accrued outside of the taxing jurisdiction. Thus, an odometer-reading-based system would also preclude other policy objectives such as allocating revenues based on where travel occurs. On the other hand, a system that enables advanced pricing strategies, permits local retention of revenues, and facilitates a rich menu of value-added capabilities that maximize system infrastructure would be substantially more complex. Such a system would likely need the ability to determine exactly which roads (and possibly at what times of day) a vehicle has traveled; which would mean the equipping of vehicles with on-board units (OBUs) that locate the vehicle and communicate with a back office. This system would be a significantly greater investment and commitment to technology but would, in theory, permit the economically efficient use of roadway capacity.

Table 1: Potential Mileage-Based User Fee Policy Objectives

Policy Objective	Definition
Revenue Generation	Address erosion of fuel tax revenues; provide a sustainable basis for transportation funding.
Economic Efficiency	Encapsulate a “user pays” principle by directly linking charge to road use; send price signals that match charge to cost imposed on roadway system by the user. To be evaluated relative to gas tax.
Charging Fairness	Accurately measure road use and charge for only miles driven on taxable roadways.
Revenue Reallocation	Redistribute revenues to jurisdictions based on actual road use.
User Privacy	Ensure that users are not “tracked.”
Data Security	Protect data from theft or interception.
System Reliability	Guard system against going offline; minimize damages of offline events with data backups.
User Ability to Audit	Provide users with a breakdown of how charges were assessed.
System Flexibility	Ensure system can accommodate future vehicle technologies, changes in rate schedule, changes in network map, and changes in roadway network topography.
Operating Reliability	Ensure that data uploads happen as needed for proper system operation.
Enforcement	Guard against user evasion or tampering.
Value-Added Options	Serve as a platform for other services that share system cost burden and offer users additional functionality.

A second reason why prioritization of policy objectives is needed from the outset is that some objectives are in competition, such that trying to design a system to achieve all would be a non-starter. For instance, many system designs seek to compute charges on board vehicles with the goal of protecting user privacy. Such a system design, however, diminishes user ability to audit as it is more difficult to furnish users with a detailed breakdown of how charges have been assessed. It is thus an imperative that policymakers weigh in on the desired features of a mileage-based user fee system in Texas before discussion can proceed from the logical architecture to physical architecture.

Significant advantages may exist to a system that offers parallel technology options. In such a system, users would choose between a "low-tech" option (likely odometer readings) and a "high-tech" option (some sort of OBU). In general, the low-tech track would offer greater privacy protection, while the high-tech track would feature bundled services that compensate users for the lower level of privacy[1]. Such a system could best accommodate cohorts of users with less inclination toward technology and would begin to demonstrate the principle of a mileage-based user fee. Those users who desire a wide range of services could demonstrate the viability of OBUs. An initial market could speed the development of a more robust offering of OBUs and bundled services. Gradually phasing in the high-tech track could also benefit system operators by allowing them to gain operating expertise before the high-tech system is completely online. In the long term, as a greater share of users opts for the high-tech track and operators become more adept, the low-tech track could be phased out.

Public vs. Private Roles

The ideal mileage-based user fee system will likely be designed, built, and operated by a team of public and private entities working together. There is clearly a high level of interest from entities of both types. On the public side, various governments at all levels have expressed interest. However, it is not clear whether the path to a mileage-based user fee will be more of a top-down one where the federal government legislates a system that states and localities can then tap into, or a bottom-up path in which enough states start their own systems that the federal government senses an imperative to unify them. The federal government may have less freedom to venture into what could be politically risky territory, but states may lack the resources to move to a system of this sort on their own, and it may not be cost-effective to implement a system at a smaller scale. The companion report on institutional issues offers a more thorough discussion of possible paths to adoption.[2]

The public sector could play two major roles in the establishment of a mileage-based user fee system. First, governments could codify system requirements that ensure that mileage-based user fees have a long-term place and ensure the long-term interoperability of systems. System requirements of this sort might be the domain of the federal government. The federal government could mandate that vehicles manufactured past a certain date be capable of functioning in a mileage-based user fee system and could ensure that systems developed by different states be sufficiently similar so that vehicles could travel from state to state and still be assessed a mileage-based fee. Another possible role for the government would be to guarantee user privacy. The government could pass legislation that defines what information could and could not be collected and/or transmitted off vehicles without user consent. Such a requirement might improve public acceptability of mileage-based fees but might also limit the private sector.

On the private side, the tolling industry, telecommunications industry, computer hardware and software industries, automobile manufacturing industry, and insurance industry have all expressed interest in having a role. The private sector could play four important roles in the development of a mileage-based user fee system:

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[1] A system that offers a "lower" level of privacy would almost certainly NOT permit the release of detailed travel history from the vehicle.

[2] Baker, Richard T., Ginger Goodin, and Lindsay Taylor. 2009. *Mileage-Based User Fees- Defining a Path toward implementation: An Assessment of Institutional Issues.* University Transportation Center for Mobility™, TTI. Transportation Institute, Texas A&M University System. Project # UTCM 09-39-16.

- Provide technical expertise to develop the on-board unit, data transmission, payment, and enforcement technologies needed.
- Provide the use of existing assets including data storage and telecommunication infrastructure and billing and transaction processing capabilities.
- Act as a privacy shield by performing some handling and processing of sensitive travel information, thereby averting the need for the government to handle this information.
- Offer value-added services that enrich a mileage-based user fee system.

Logical Architecture Options

The system's logical architecture provides the structure within which specific OBU and communications technologies are deployed. For clarity of discussion, the following discussion decomposes the logical architecture into three stages:

- **Roadway use assessment**: This refers to the collection of raw data describing vehicular movement. In some architectures this stage may also include some data processing and transmission; however, for purposes of this discussion, the concern is primarily data collection.
- **Charge computation**: This refers to data processing in which raw data are used to assess an amount owed. Depending on the architecture, this stage may occur entirely on board the vehicle or with functionality split between the vehicle, a back office, and potentially a third party. The discussion here will highlight the relative advantages and disadvantages of these approaches.
- **Vehicle-to-back-office communication**: This refers to transmission of data for the computation of the amount owed or the transmission of the already-computed amount owed from the vehicle to a back office. This stage also includes the communication of unit health signals to a back office that may be used to alert operators if an OBU is malfunctioning or has been tampered with.

The distinction between these three stages of the logical architecture is not hard and fast; indeed, the process flows may overlap. Nevertheless, these stages address very different technology questions and have bearing on distinct policy objectives, as Table 2 illustrates.

Roadway Use Assessment

The options for roadway use assessment represent a tradeoff between technical simplicity and the level of road use detail obtained. While there are relatively low technological ways to measure vehicle distances driven, gaining a more complete picture of roadway network use requires added technical complexity. At the most basic level, data collection could consist of a reading of total miles driven during a charging period with no information on when these miles were driven or which roadways were used. At its most complex, data collection could provide a detailed travel history including roadway network location and time stamps.

Policy objectives will determine the level of data collection required. For instance, a system designed to merely charge people for their overall use and that allows for some level of charging inaccuracy and perceived unfairness requires the least information about users' travel. On the other hand, a system intended to convey strong price signals, charge users in a completely fair and accurate manner, enable the reallocation of revenues raised to the jurisdictions in which roadways were used, and serve as a platform for the widest menu of value-added services requires considerably more information about users' travel.

Table 2: Three Stages of a Mileage-Based User Fee Logical Architecture

Logical Architecture Stage	Technology Questions	Policy Objectives Impacted
Roadway Use Assessment	What raw data are collected? What levels of spatial and temporal accuracy are needed?	Economic efficiency User privacy Charging fairness System reliability Revenue reallocations Value-added options
Charge Computation	Where are data processed? What data may leave a vehicle? Where are data stored?	User privacy User auditing capability Data security System flexibility Operating reliability Value-added options
Vehicle-to-Back-Office Communication	How often are data uploaded from vehicles? What is the scale of data transmission?	System reliability User privacy Data security System flexibility Enforcement Operating reliability Infrastructure costs Operating costs Value-added options

Prior public acceptability research indicates that to be perceived as a legitimate user fee, a mileage-based user fee will need to charge appropriately for distance traveled by individual road types, protect privacy, account for limited public transportation options, allow for local retention of revenue, and address out-of-state and out-of-region travelers. All of these criteria suggest a need to know which roadways users have driven on. Without location data, the fair discounting of miles driven out of state or on non-taxable roads is infeasible. Similarly, the reallocation of revenues to local jurisdictions on the basis of actual roadway use is impossible without a record of where miles were driven.[3] Finally, not having location or time-of-day data precludes a number of value-added services.

Architecture Options

Architecture 1: Odometer Distance Measurement

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[3] However, there are other ways to achieve a mileage-based revenue reallocation. Reallocation could be based on lane-miles per jurisdiction or based on sampling drivers and then utilizing formulas based on that sampling to allocate revenue to local entities. Lane-mile based reallocation, however, is not usage based and creates the potential for funding mismatches when capacity does not reflect usage (demand). A reallocation based on sampling the actual road usage of some drivers may be an attractive alternative. Practically, the assembly of a completely representative sample and the development of reallocation formulas could present issues: it may be difficult to capture some cohorts of drivers, and formula design could turn political. Incorporating all drivers into a mileage-based user fee system, while a much more costly and longer-term undertaking, could ensure that revenue reallocation is done in an apolitical manner that considers all drivers.

Certified odometer readings provide direct, reliable, and high accuracy distance measurement. From a logical architecture standpoint, the significant drawback of odometer distance measurement is the lack of information on which roadways were used and when miles were driven. Thus, while distance measurement may be accurate, charging accuracy may be considerably less. Odometer readings would offer some improvement in economic efficiency over the gas tax by directly linking the usage fee to roadway consumption; however, the inability to match the fee to the magnitude of cost imposed on the roadway system (i.e., difference in social cost of driving by facility used and time of day) means full economic efficiency is not attained.

It is possible to tamper with odometers; indeed, by some estimates "clocking" or "rolling back" costs over $4 billion annually.[4] Odometer tampering is illegal under federal law, however, and certified mechanics are often able to detect signs of tampering.

Architecture 2a: Vehicle Speed-Based Distance Measurement

Data on vehicle speeds can be used to back calculate miles driven. This method entails feeding a detailed record of vehicle starts, stops, and speeds collected at time intervals during the trip (e.g., 1 second intervals or less) into a distance computation algorithm. The distance computation algorithm then provides trip distances. The most obvious advantage of this approach is that trip distances can then be sent electronically to a back office, eliminating the administrative burden of manual odometer readings. The conversion from speed data to trip distances can be performed on board the vehicle (as shown in Figure 2) or in a centralized facility (in which case speed data would be uploaded from the vehicle).

In theory, any technology that generates a high temporal resolution record of vehicle speeds is an option for this technique. One highly discussed option is to use a connection with a vehicle *on-board diagnostic (OBD) port* (as illustrated in Figure 2). An OBD port, or diagnostic bus, is found in all post-1996 vehicles and provides information on major engine components used for testing emissions and diagnosing engine problems. Connections with the OBD port can be achieved simply with "plug and play" devices. In fact, the use of OBD ports to obtain driving data has already been demonstrated by some insurance companies that have installed memory modules in the vehicles of participating customers to assess premiums based on drivers' actual speeds and time-of-day or road use.[5]

The use of vehicle speed data provides high accuracy distance measurement. Distance measurement reliability is high because all connections are within the vehicle. Because the data set assembled has time stamps, this approach would also enable time-of-day specific congestion pricing and value-added services that make use of this information (e.g., rewards for off-peak driving). A significant disadvantage of this approach is that it does not generate location information. The lack of knowledge of which roadways were used compromises charging fairness and revenue reallocation.

Another disadvantage of using connections with OBD ports is that, while there is some standardization of OBD output, there is no standard OBD design. OBDs have different power requirements and interfaces, and a device designed to connect with the OBD port would need to be adaptable to all makes and models. In the long run, standardized OBD ports could be built into new vehicles; however, if vehicles already on the road are to be outfitted with OBD-connected devices, the non-uniformity of OBDs will prove to be a difficulty. Connection with the diagnostic port is not an option for all pre-1996

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[4] http://www.securityworld.com/ia-55-odometer-tampering.aspx

[5] For instance, Progressive's MyRate program: http://www.progressive.com/myrate/

vehicles and would require a certified installation. Manufacturing and installing OBUs that connect to the diagnostic port would almost certainly be higher cost than a simple odometer reading.

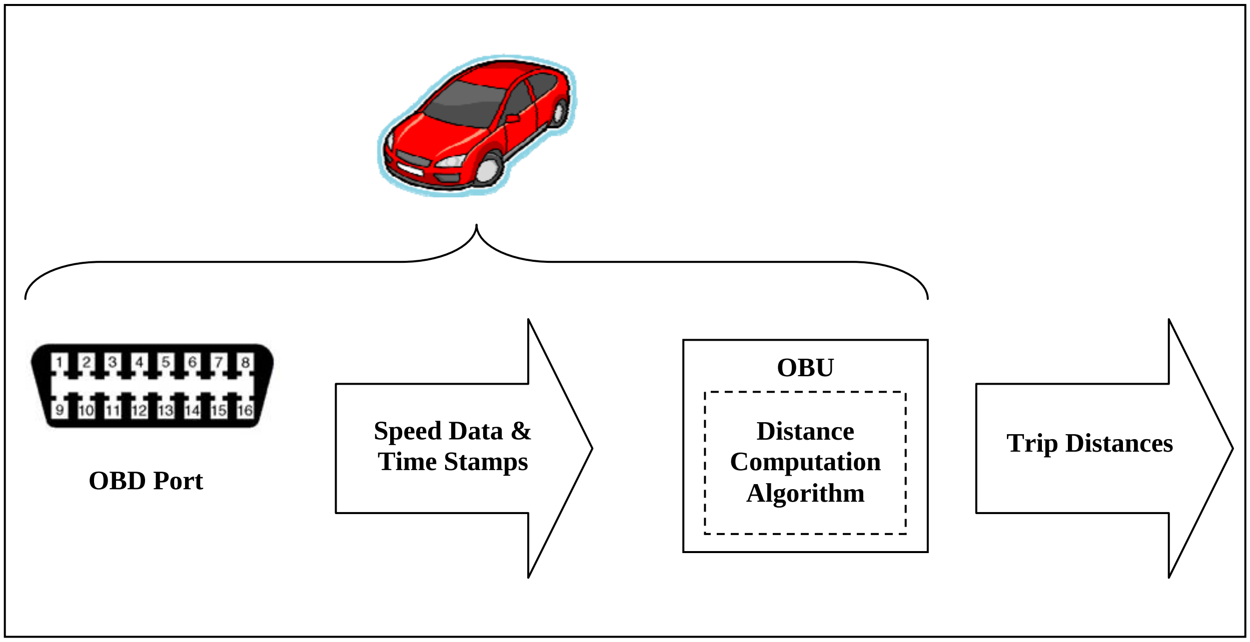

Figure 2: Architecture Utilizing the Conversion of Speed Data to Trip Distances

Architecture 2b: Vehicle Speed-Based Distance Measurement with Beacon-based Location-stamping
This approach is best thought of as a subset of the speed-based distance measuring approach in which data are appended with location-stamps; the addition of location-stamps provides some capability to discern where miles were driven that is otherwise absent with speed-based distance measuring (Figure 3). This approach requires a network of roadside location beacons that identify travel zones.[6] Vehicles would be outfitted with an OBU that constantly searches for the nearest beacon. Upon identification, that beacon's unique identifier would be attached to the data set. The transmission of location-stamps could be independent of the upload of travel data to a back office, or these could use the same data transmission line.

A key logical architecture requirement for this arrangement is a network of location-marking beacons that have distinct locations, cover the entire roadway network, and maintain a constant line of communication with vehicles. Cellular phone towers have been suggested as an option capable of meeting these logical requirements.[7] Existing cellular phone networks cover much of the roadway network and penetrate through many so-called urban canyons (bridges, tunnels, and dense urban environments where satellite signals become distorted). Cellular phone towers could thus provide a good degree of charging reliability. Other technologies may meet the logical requirements of this architecture but would likely mean building an entirely new infrastructure.

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[6] Travel zones are polygons superimposed on the roadway network that could be used to recognize state boundaries, jurisdictional boundaries, or charging cordons.

[7] Donath, Max, Alec Gorjestani, Craig Shankwitz, Richard Hoglund, Eddie Arpin, Pi-Ming Cheng, Arvind Menon, and Bryan Newstrom. "Technology Enabling Near-Term Nationwide Implementation of Distance Based Road User Fees." Report Number CTS 09-20. University of Minnesota Center for Transportation Studies. June 2009.

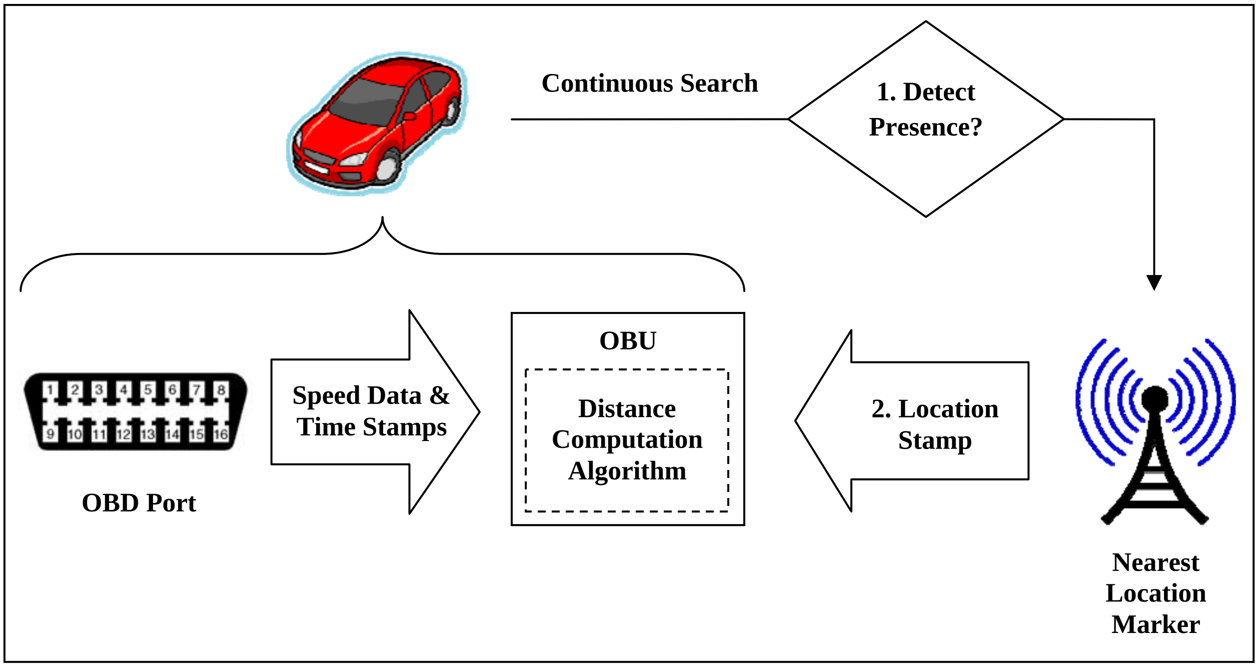

Figure 3: Architecture Utilizing the Conversion of Speed Data to Trip Distances with Beacon-Based Location-Stamping

A beacon-based location-stamping approach does not provide exact vehicle positions but rather knowledge of what times a vehicle traveled on certain facilities or within certain travel zones. The resolution with which roadway network use is known is proportional to the density of location-stamping infrastructure. At high densities of beacons, zones could be defined more precisely (more, smaller zones as opposed to fewer, larger zones) and vehicles could be identified as traveling within certain post-miles of a facility (as opposed to merely traveling on the facility). The range of cellular phone towers, for instance, varies depending on the terrain. If using an existing cellular phone network for location stamping, the precision achieved would likely be sufficient to identify vehicles as driving in or out of State, and to identify county boundaries. This approach could thus correct one of the main sources of charging inaccuracy in speed-based distance measurement and assist in the reallocation of revenues to the proper jurisdictions. However, the location-determining accuracy from this approach would likely not be sufficient to distinguish miles driven on private roadways and may not be able to discern finer-grained jurisdictional boundaries (e.g., different municipalities within an urban region). Charging fairness and ability to properly reallocate revenues would therefore not be complete. The lack of complete location identification would also impede some value-added services and capabilities, such as lane-based tolling and parking finding.

Architecture 3: Detailed Time and Location-stamping

A final approach to characterizing roadway use is to construct a complete record of where miles were driven. In such an approach a wide-area communications technology is used to continuously broadcast sets of location coordinates to vehicle OBUs (Figure 4). Vehicle OBUs triangulate from these coordinates to determine the location of the vehicle. Vehicle location coordinates are then matched to a network map to determine specific network use. Map matching can occur on board the vehicle (as shown) or after data are uploaded from the vehicle (in which case only raw location coordinates would be transmitted). Map matching can be performed on a facility basis (matching the location to a specific road) or a zonal basis (matching the location to a spatial polygon within the jurisdiction).

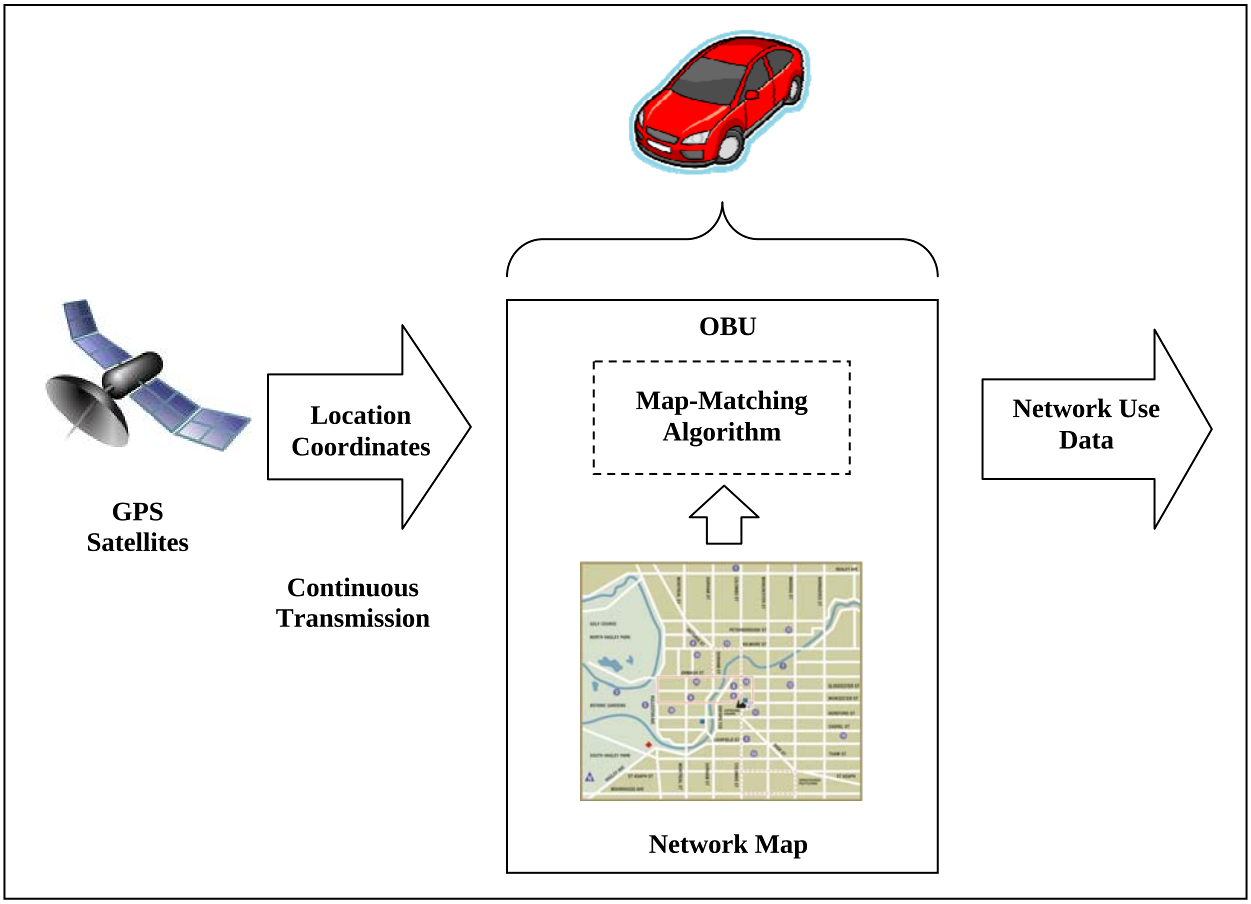

Figure 4: Architecture Detailed Time and Location-Stamping

In theory, any technology that remains constantly in touch with vehicles and provides a stream of sets of coordinates for vehicle positioning is workable for this architecture. The obvious candidate is global positioning system (GPS) satellites. This architecture could be adapted to a wide variety of communication technologies to upload data from the vehicle to a back office.

The significant advantage of this approach is that it would generate a complete record of vehicle movement. On the other hand, there may be accuracy and reliability tradeoffs. For instance, measuring distances traveled based on triangulated location coordinates can result in inaccuracies. There are, however, corrective algorithms that ensure that even if location coordinates are not accurately identified, distances driven are measured within a tolerable range of accuracy. Reliability may also be an issue with wide-area communications-technology-based positioning. In some dense urban canyons or tunnels where signals do not penetrate, devices may go offline. Atmospheric disturbance can also cause long-range data transmission to fail. Again, there are solutions to this problem that involve imputing miles based on the data from before and after the signal loss.

Texas' Needs

Table 3 shows a comparison of how well the various roadway use assessment system architectures discussed might address potential mileage-based user fee system policy and program goals. Ultimately, the need to exclude miles driven on out-of-state[8] and private roads from being charged, as well as the problem of fairly allocating revenues to the jurisdictions in which road use occurred, will likely require the use of an architecture that identifies where miles were driven in some way. These were key points in focus groups conducted in rural northeast Texas. [9] Motorists who drive routinely on private farm roads or make one or more long-distance driving trips resented the idea that they might be charged for these miles. Many small localities, especially rural ones that feel outmuscled for transportation funding by larger metropolitan areas, were particularly receptive of the idea that a mileage-based user fee would ensure that they are adequately compensated for miles driven on their roads. Without the enhanced local revenue retention, a mileage-based user fee will be substantially less attractive for these focus group participants.

Table 3: Comparison of Roadway Use Assessment Architecture Options

	Odometer Reading	Speed-Based Measurement	Speed-Based Measurement w/ Location Stamping	Detailed Time and Location Stamping
Information Known				
Distance Driven	Full	Full	Full	Full
Time Stamp	None	Full	Full	Full
Location Stamp	None	None	Partial	Full
Roadway Used	None	None	Partial	Full
Accuracy	High	High	High	Moderate/High
Economic Efficiency	Low	Moderate	Moderate	High
User Privacy	High	Moderate	Moderate	Low
Charging Fairness	Low	Low	Moderate	High
System Reliability	High	High	High	Moderate
Revenue Reallocation	None	None	Moderate	High
Value-Added Options*	None	None	Moderate	High

* = Value-added potential also depends on charge computation and vehicle-to-back office architecture.

Detailed location and time stamping (Architecture 3) would certainly provide the level of location data needed to meet these policy criteria. A speed-based distance measurement approach with beacon-based location stamping (Architecture 2b) could be used to determine when state and county boundaries are crossed (to ensure that out-of-state miles are not charged and to enable revenue reallocation). However, it is difficult to envision this approach working as a way of determining when private roads are used. On the other hand, a compromise solution might be reached in which drivers who expect they will accrue significant miles on non-taxable roads are credited back their expected daily driving on these roads. It might also be possible to augment the location-identifying abilities of cellular

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[8] Drivers could theoretically be required to stop at the state border to register their odometer reading; this would prevent charging for out-of-state miles and would ensure participation by out-of-state drivers passing through Texas, but it would also represent a new cost and burden on drivers. In addition, the problem of distinguishing between public and private roads would still remain.

[9] Baker, Richard T., Ginger Goodin, Eric Lindquist and David Shoemaker. 2008. *Feasibility of Mileage-based User Fees: Application in Rural/Small Urban Areas of Northeast Texas.* University Transportation Center for Mobility™, Texas Transportation Institute, Texas A&M University. UTCM Project # 08-11-06.

towers by placing roadside readers that flag a vehicle as having passed at key locations (for instance, at the boundaries of a jurisdiction, a tolling cordon, or the on- and off-ramps of a freeway section).

A related key issue is how much positioning accuracy Texas really needs. The answer to this question requires foresight as to how advanced of a policy the mileage-based user fee is intended to be and what sorts of other applications the system might be supported. A system in which the mileage-based fee is designed to support congestion pricing could require a very high-level accuracy (within 10 feet for lane-based tolls or urban cordons that need to be accurate to the city block level). Many other value-added applications may also require a high level of accuracy (e.g., parking finders).

Charge Computation

Charge computation constitutes the second stage of the logical architecture. Charge computation consists of the data processing in which miles driven are calculated from raw vehicular movement data, miles are sorted by charging class, and a rate schedule is applied to compute a charge owed.[10] Generally speaking, the options in this stage favor either user privacy or ease of user auditing and a greater number of value-added options. A system that allows an extremely limited amount of information to be transmitted off board the vehicle would maximize user privacy. This is a technical possibility: vehicles could be outfitted with an OBU that only transmits an amount owed. On the other hand, a system that allows more information to be transmitted off board the vehicle would permit billing offices to furnish drivers with a more detailed breakdown of how charges were assessed. Similarly, systems allowing more information off board the vehicle will dramatically increase options for value-added services such as real-time routing information and parking location services. Allowing more information off board the vehicle also increases the potential utility of the system for governmental entities (e.g., for household travel surveys or speed surveys).

Architecture Options

Architecture 1: Thin-Client Data Transmission

The most basic architecture is often referred to as "thin client" because a low level of functionality exists at the decentralized client (vehicular) level. In this architecture, OBUs merely collect data, which are then sent directly to a centralized back office (Figure 5). Data processing and storage happen at the back office. Information is not necessarily sent in real time. The detailed travel information could be compressed and sent at some periodic uploading interval (in other words, fears of "tracking" are unfounded, even with this architecture). Nevertheless, the essence of this architecture is that the full record of when and where travel has occurred is maintained until after the travel information is uploaded from the vehicle.

This configuration provides minimal privacy protection. A thin-client configuration would be problematic if the back office is publically run, as this would require government handling of individuals' detailed travel information. It is questionable whether individuals would tolerate even a private entity handling their detailed driving history if not given an option to opt out.

This configuration provides easy user auditing, as providers can offer detailed bills with a full breakdown of how charges have been assessed. Data security is comparatively lower because of the transmission of sensitive information, but the centralized storage of this information enables an economy of scale of data backup. This configuration also enables a wide variety of value-added services because

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[10] Charging classes could be distinguished based on jurisdiction, facility type, roadway conditions (i.e., congestion pricing), or other bases.

operators/providers have full travel information. A final advantage is that this configuration requires the least computationally complex OBU; in theory, the OBU requires nothing more than an OBD plug-in or GPS unit, the ability to store coordinates, and a communication link to the back office. The system provides a high level of flexibility because changes to the network map and rate schedule need not be communicated to all vehicles. Because data storage is largely centralized, system reliability is lower because failure at a single point (the back office) could result in severe data loss.

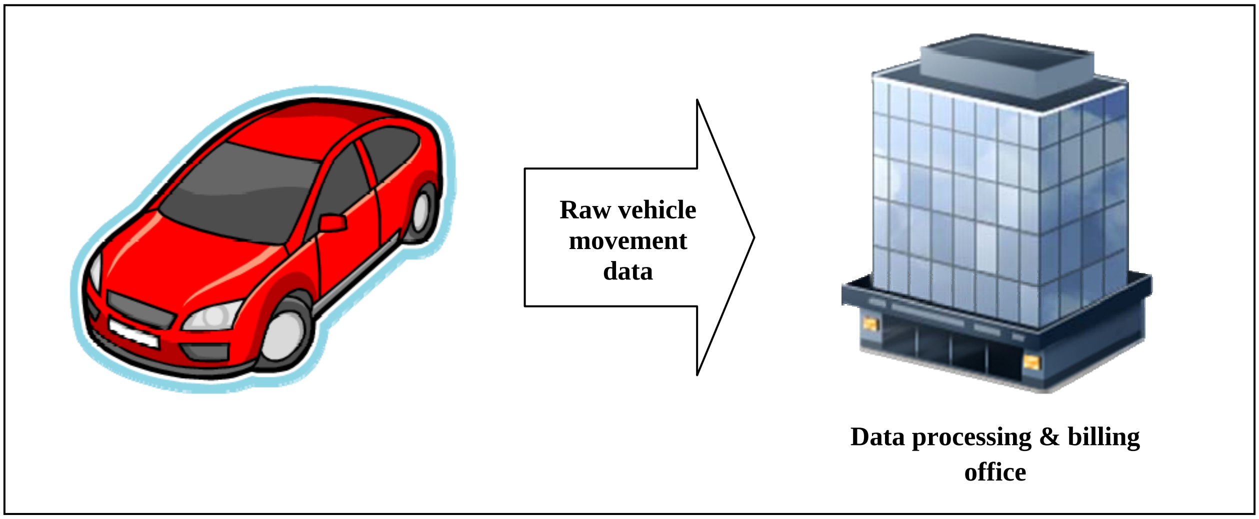

Figure 5: System Architecture Featuring "Thin Client" Data Transmission

One important note is that manual odometer readings are actually the "thinnest client," as with this architecture there would be zero on-board functionality aside from the odometer itself. Despite both configurations (manual odometer reading versus data transmission of data to a back office) being thin-client architecture, they perform very differently with respect to key policy dimensions. Manual odometer readings offer a high level of privacy protection, as no sensitive information is ever collected.[11] User ease of auditing and data security are moot issues with odometer reading because users can easily see how much they have driven and there are no data produced that are not already present in the status quo. On the other hand, using odometer readings would rule out all value-added services, and odometer readings may compromise other policy objectives, as discussed in the Roadway Use Assessment section.

Architecture 2: Thick-Client Data Transmission

In a thick-client architecture, most functionality is shifted to the decentralized client (vehicular) level. OBUs are "smart," meaning that they perform most data storage and processing on board before uploading information (Figure 6). OBUs could perform different levels of data processing. In one much-discussed configuration(such as the system tested by the Oregon Department of Transportation), the OBU would aggregate all of the miles by charging zone or type of facility on board and would allow only these totals off the vehicle. This level of data processing would require the vehicle to have an on-board map. Another configuration discussed would compute the entire charge on board. The OBU would

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[11] Practically speaking, the privacy differences between manual odometer readings and a thick-client architecture (discussed later) may not be significant, as in a thick-client architecture the privacy level can be set such that no sensitive information leaves the vehicle; the only potential privacy difference would result from the low risk of an individual OBU being hacked.

apply a rate schedule stored on board to the different classes of mileage totals and send only the amount owed to the back office.

This architecture enables a high level of privacy and data security. No sensitive information is transmitted or handled by the back office. Because a considerable amount of data storage is done by the OBUs, each OBU would be required to have its own data backup mechanism (i.e., the centralization of data storage and redundancy of the thin-client architecture is not present). On the other hand, the risk of failure at a single point is greatly minimized by the distributed storage scheme, contributing to a high level of system reliability.

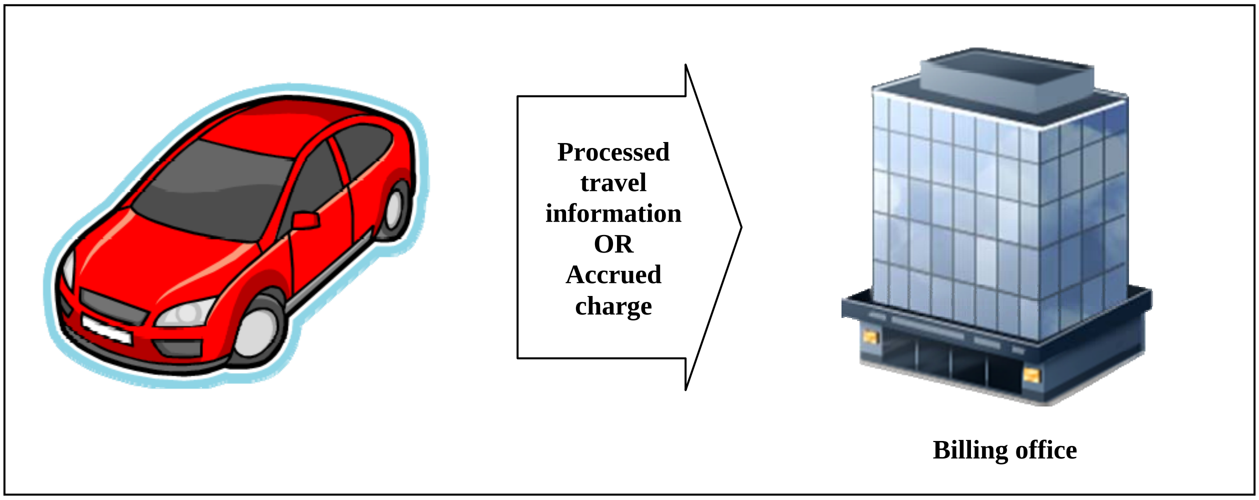

Figure 6: System Architecture Featuring "Thick Client" Data Transmission

A significant drawback is the loss of a number of potential value-added services. A number of the more attractive value-added options require knowledge of not just what types of roadways a driver uses, but also when and which specific roadways are traveled. This information would be unavailable in a thick-client architecture. Users' ability to audit in this architecture is lower, as much of the bill is computed on board. Depending on how much of this computation is done within the vehicle, providers may not be able to offer any explanation of the bill. Providers would likely need to build the ability for users to view their travel history into the OBU to make this architecture acceptable from a user fairness standpoint.[12] Another major drawback of this architecture is the need to update every individual vehicle's on-board map and rate schedule whenever these change. Theoretically, this could be performed through the data transmission avenue that is used to upload data from the vehicles. In practice, it could prove quite costly to update every vehicle, thereby hampering system flexibility. In settings in which the network map and rate schedule are relatively static, however, this will not prove to be a great disadvantage.

Architecture 3: Third-Party Intermediary Data Transmission

The key feature of this architecture is a third-party entity that acts as a privacy shield. The OBU complexity in this architecture is low, as in the thin-client architecture. A third party collects detailed travel data from vehicles, processes the data, and then sends aggregated travel information or an amount owed to a billing office (Figure 7). This architecture preserves full travel data that third-party

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[12] One option is to maintain a previous month's travel data in the OBU. If a user wanted to dispute a charge, he or she could then authorize the downloading of this data for auditing purposes.

entities can use to offer value-added services. Under this architecture, there is the potential for a competitive market of third-party entities that compete on the basis of cost and value-added services.

This architecture does not pose the OBU updating problems of a thick-client architecture because network maps and rate schedules do not necessarily need to be stored on board. System flexibility is thus high and a moderate level of user auditing capability is enabled. For example the third party entity in charge of data processing could forward some information needed to provide a more detailed charge breakdown to billing offices. The architecture provides a greater level of privacy protection than a thin-client architecture because the entity in charge of billing never sees a detailed travel history. Users could potentially choose among several providers with one of their considerations being who they trust most. While privacy improves, data security risks are similar to those of a thin-client architecture because sensitive information is transmitted off the vehicle.

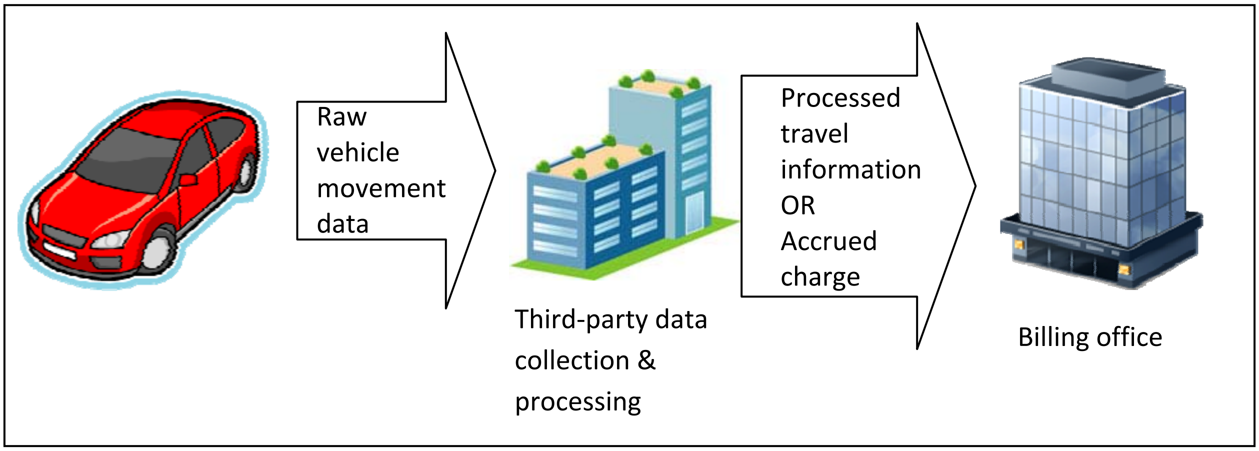

Figure 7: System Architecture Featuring Third-Party Intermediary Data Transmission

Implicit in this architecture is the assumption that the public trusts a non-governmental entity with its sensitive travel information. As one interviewee pointed out, under new privacy protocols adopted in the European Union (EU) that do not permit any travel information off board, this architecture is not permissible.

Architecture 4: Opt-In Third-Party Intermediary Data Transmission

This architecture is essentially a hybrid of the thick-client and third-party intermediary architectures (Figure 8). Drivers may opt-in to a track operated by a third-party intermediary in which they consent to the release of their driving history in exchange for value-added services. This architecture might be thought of as analogous to the postal industry in which the United States Postal Service exists as a public provider charged with ensuring uniform pricing and delivery to all parts of the country, but several major private providers offer alternatives for those customers desiring faster delivery or a more cost-effective option for their particular needs. Those drivers opting out of the base track would face a lower level of privacy protection, but this configuration would not force any driver to release any detailed travel information. Privacy, user ability to audit, data security, and availability of value-added services in the base track and opt-in track are similar to those in the thick-client and third-party intermediary architectures, respectively.

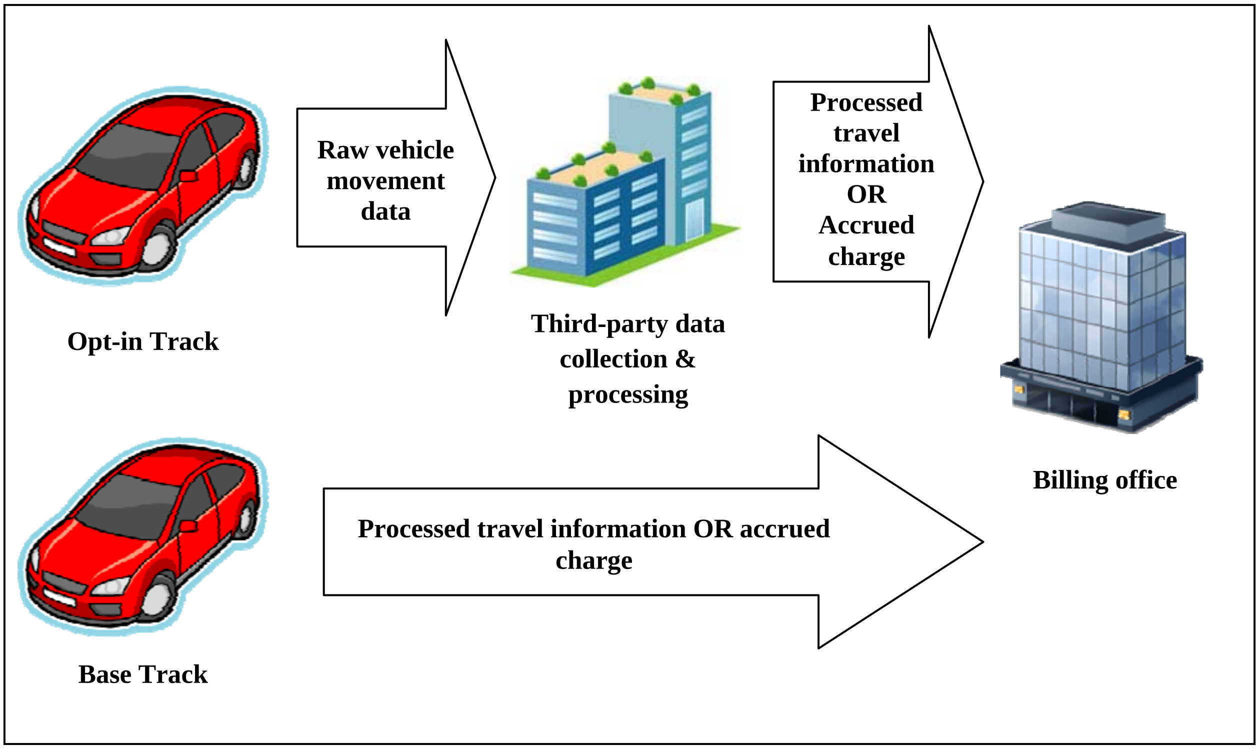

Figure 8: System Architecture featuring Opt-In Third-Party Intermediary Data Transmission

Architecture 5: Anonymous Loop-Back Proxy Data Transmission

In the anonymous loop-back proxy configuration (figure 9), the map and rate schedule are stored off board. Vehicles store detailed travel information on board, but all data processing and charge computation are performed by off-board price calculators. When a vehicle needs to upload charge information to the billing office, it first sends detailed travel information to the price calculator, which applies the current map and rate schedule to compute a charge. The charge data are then sent back to the vehicle and finally to the billing office.

This architecture provides maximum privacy protection because the detailed travel information that is used to compute the charge is transmitted anonymously. A further advantage of this architecture is flexibility in the network map and rate schedule. Changing or updating these components requires updating only centralized price calculators; all vehicles then tap into these centralized price calculators. A thick-client architecture, in contrast, provides a similar level of privacy protection but requires that all updates to the network map or price calculator be disseminated to all vehicles. This architecture is thus highly advantageous for dynamic pricing applications.

Data security is potentially low, as detailed travel information is transmitted off the vehicle. System reliability is high because the consequences of failure at a single point are minimized by the largely distributed data storage. While this architecture is not specifically designed to support value-added applications, opportunities exist for the off-board price calculator to support some applications, such as pay-as-you-drive insurance or parking payment. As in the thick-client architecture, OBUs would likely need to be designed with the ability for users to view their driving history, as billing entities are not furnished with adequate information to provide a detailed billing statement. A final possible drawback to this architecture is an increased number of data transmissions. Depending on the data

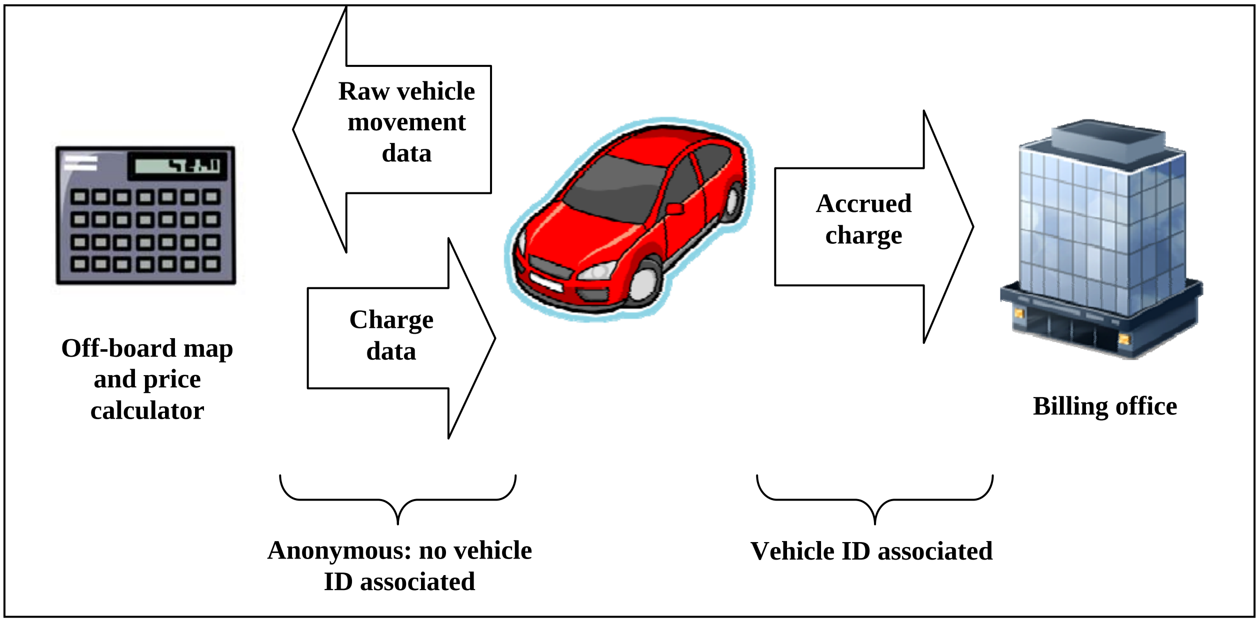

Figure 9: System Architecture Featuring Anonymous Loop-Back Proxy Data Transmission

transmission technology used, this could greatly increase system operating costs. In the deployment scenarios in which this architecture makes most sense, however, there may be chances to use technologies in which operating costs do not vary greatly with the number of transmissions. As discussed in the Data Transmission Issues section, in the urban environments in which one might expect the network map and rate schedule to change more frequently, these sorts of data transmission technologies may be highly practical.

Table 4 below summarizes the performance of different system architecture types in important policy objective categories.

Table 4: Comparison of Charge Computation Logical Architecture Options

System Architecture	Thin Client	Thick Client	Third-Party Intermediary	Opt-in Third-Party Intermediary	Anonymous Loop-Back Proxy
User Privacy	Low	High	Moderate	Moderate/High	High
User Ability to Audit	High	Low	High	High	Low
Data Security*	Low	High	Moderate	Moderate/High	Low
System Flexibility	High	Low	High	High	High
Operating Reliability	Low	High	Low	Moderate	High
Value-Added Options	High	Low	High	High/Low	High

* = Data security is greatly determined by data transmission technology used as well as system architecture; it is possible to rectify low security architectures and technologies by using secure encryption methods.

Data Storage Needs

Data storage can be achieved either on board or at a centralized back office, depending on system architecture. Data storage must be secure and redundant. In other words, data should be stored in such a manner that it is protected from hacking, leakage, or system shutdown.

Storage achieved on board is essentially free because of the low cost of computer chips and the availability of data compression techniques. On-board storage, as in a thick-client or anonymous loop-back proxy architecture, also provides built-in data security because of the low likelihood that individual vehicles would be hacked. Redundancy would need to be designed into on-board units, but the low cost of storage makes this very possible. If storage is achieved on board, procedures for dealing with cheating and equipment failure will also need to be developed.

Centralized data storage, as in a thin-client or third-party intermediary architecture, requires large file servers. The cost will be higher because centralization of data storage increases data security risks. Cost will reflect the market rate for bulk data storage. Numerous companies already maintain large file servers, and the marginal cost for these entities to host mileage-based user fee data storage could be low. It may thus prove advantageous to engage the private sector to manage back-office data storage.

Vehicle-to-Back-Office Communication

Vehicle-to-back-office communication is the final stage of the logical architecture. In this stage two sorts of data packets—travel data used to compute a charge or the amount owed itself (depending on the charge computation architecture) and unit health signals—are uploaded from the vehicle to a back office. In some architectures, the upload may actually go to a third party (though all of the architectures are presented here without a third-party entity). The vehicle-to-back-office communication determines when data are offloaded from the vehicle. In general, more frequent data upload and the ability to accommodate on-demand uploads ensure greater system reliability and enhance enforcement but also drive up operating costs.

Architecture Options

Architecture 1: Manual Reading

The most basic form of charge reporting would involve manually reading travel data or a charge owed from the vehicle. This architecture would likely exist only with odometer-based roadway use assessment. In this architecture, drivers would take their vehicles to a certified outlet and distances driven would likely be sent to a billing office (where charges would be computed). Because manual readings place a burden on drivers to take their vehicles in for charge reporting, data upload would likely need to occur with a low frequency (for instance, annually or semiannually). If coupled with vehicle registrations, the illegality of driving with an expired registration would provide a built-in enforcement mechanism that could keep compliance at a reasonable level. Infrastructure and operating costs in the case of manual readings could be low due to potential synergies with the Department of Motor Vehicles, which already has a system in place for collecting and aggregating information and billing motorists. Data security is a non-issue with odometer readings, as no sensitive travel data is produced. It is difficult to envision any value-added services resulting from manual readings.

Architecture 2: Localized, Detection-Based Transmission

A localized, detection-based transmission architecture requires the deployment of a network of roadside readers that download data from vehicles and then forward that data to a back office (Figure 10). Data transmission happens over relatively short distances (on the order of 100 feet to 1000 feet) and is contingent upon detection of the vehicle (i.e., the vehicle passing within range of the reader). Readers could be mounted on traffic signals, highway signs, overpasses, gas pumps, or simply roadside. A variety of technologies are suitable for the short-range vehicle-to-infrastructure communication featured in this architecture including dedicated short-range communications (DSRC), wireless local area networks (WLANs, chiefly Wi-Fi), and Zigbee. Communication from the reader to the back office would likely occur via a landline connection. The most likely scenario for these technologies would be a contract with some entity to build (and possibly operate and maintain) the needed infrastructure.

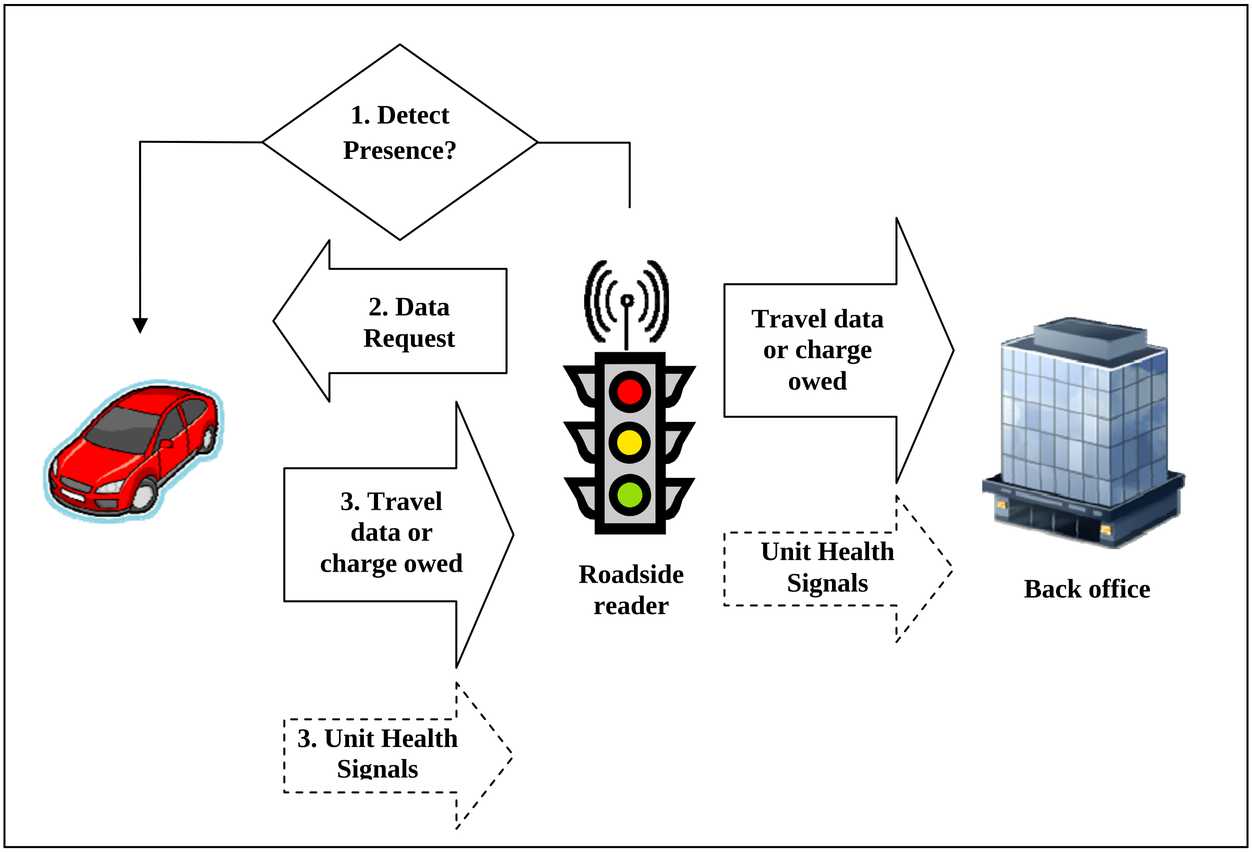

Figure 10: System Architecture Utilizing Localized, Detection-Based Transmission

The temporal frequency of data upload in this architecture depends on how often vehicles pass by roadside readers. A higher density of roadside readers will increase the probability that drivers pass a reader, and there are opportunities to strategically place readers to maximize coverage. Nevertheless, it is difficult to envision a cost-effective way to achieve statewide coverage of Texas' extensive road network. The large numbers of rural drivers in Texas would make the coverage problem particularly acute. This means there is a chance in a localized, detection-based transmission architecture that data upload from some vehicles might not occur when needed for prompt billing or detection of a malfunctioning OBU. Even if complete coverage of the road network could be achieved, a driver who parks his or her vehicle for an extended period of time could present a similar impediment to timely data upload. The impacts of these two considerations on system reliability and enforcement may mean that localized, detection-based data transmission is not a suitable option for vehicle-to-back-office communication. On the other hand, with respect to data transmission, frequent (i.e., more often than weekly) data upload may only be necessary for advanced value-added applications. If it is acceptable that unit health signals not be uploaded expediently, a design using localized, detection-based transmission that relies upon the high probability that drivers will all pass a few common points during a week might be possible.

Localized, detection-based data transmission presents relatively low data security risks because the short transmission distances minimize opportunities for interception. System flexibility is lower than in other vehicle-to-back-office communication architectures because of the need to build new readers as the road network expands or patterns of utilization change. Infrastructure costs are likely high (relative to other vehicle-to-back-office communication options) due to the need to build new infrastructure. In contrast, operating costs are relatively low: data transmission using localized technologies is tantamount to a file download, making it relatively cheap, regardless of amount of data sent; the primary operating costs would be the maintenance and replacement of roadside readers.

A major advantage of this architecture is its suitability to a variety of safety and traveler information-related value-added applications, such as in-vehicle signing or warning messages. These sorts of applications are particularly appropriate because the localized nature of the data transmission can be used to filter out irrelevant vehicles. Rather than sending an in-vehicle sign to all vehicles within Texas, for instance, a localized technology can send the sign to only those vehicles that will pass by the stretch of roadway to which the sign pertains. Many safety applications also require the ability to communicate vehicle-to-vehicle, a function best achieved by localized technologies.

One caveat is the potential for next-generation reader technology to drive down infrastructure costs of localized data transmission technologies. Localized technologies such as DSRC were originally conceived of as best deployed through a distributed network of small-scale readers placed along the roadside. Building this sort of physical infrastructure for the entire state of Texas is almost certainly cost prohibitive. One possibility might be to rethink the scale of readers. Large numbers of drivers could be reached with a few high-capacity readers that are placed in strategic locations, such as freeway interchanges or the intersections of major arterials. Another possibility to make localized data transmission technologies cost effective is mesh networking. In a mesh network, vehicles would form an ad-hoc network in which each vehicle is a node. A message originating at roadside infrastructure could be carried to other vehicles via vehicle-to-vehicle communication. Successfully using mesh networking would require a high level of penetration of OBUs with localized communication ability, but in the long term it could provide the sort of flexibility to network topography changes that a system based purely on roadside infrastructure lacks while reducing the need for roadside readers.

Architecture 3: Wide-Area, Constantly Online Transmission

A wide-area, constantly online architecture uses a network of readers that download data from vehicles within a large radius and forward the data to a back office. A crucial feature of this architecture is the maintenance of a constant line of communication between the vehicle and reader (and thus back office). While the actual temporal frequency of data upload depends on system operators, this could theoretically reach a constant transmission of data packets. This architecture is designed around a technology that provides ubiquitous coverage and transmits data over relatively long distances (on the order of 1000 feet to 25 miles). The likely technology for vehicle-to-reader communication in this architecture is a cellular-based technology, such as global system for mobile communications (GSM). GSM networks are available in nearly all areas that drivers will travel in Texas and are always online. A probable operating scenario would be to contract with a telecommunications company to use existing cellular infrastructure. Tower-to-back-office communication could occur through a landline connection.

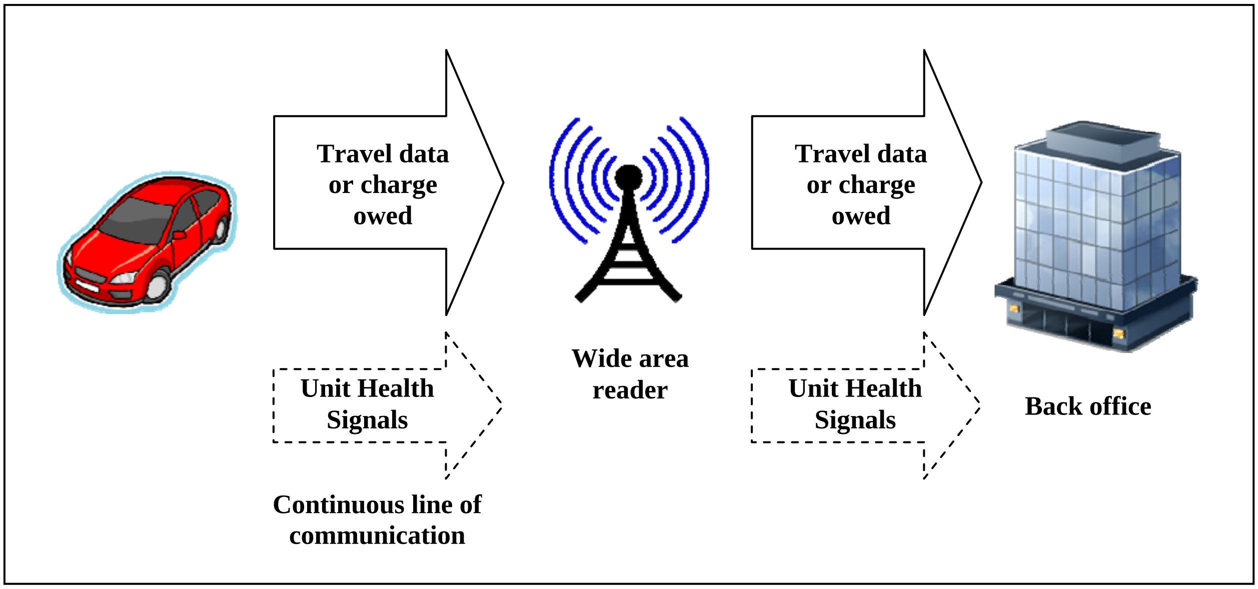

Figure 11: System Architecture Utilizing Wide-Area, Constantly Online Transmission

The constant line of communication between vehicles and the back office enables a high degree of system reliability and enforcement capability: vehicles can be programmed to offload charge data at some specified time and to send a unit health signal immediately after any malfunction. Data security may be lower than in localized transmission due to the long transmission distances; however, strong encryption methods can minimize this risk. Flexibility to changes in roadway network topography is high because the same cellular towers can be used even as the road network changes. Infrastructure costs are relatively low with this architecture because of the potential to use existing cellular infrastructure. On the other hand, operating costs could be quite high: wide-area data transmission is tantamount to sending a text message or placing a phone call, which is considerably more expensive than a file download.

Wide-area communication technologies are well adapted to mobility improvement value-added applications such as real-time routing or dynamic roadway pricing because these require vehicles to maintain constant communication. Parking location applications also require that a vehicle be capable of communicating its position at the beginning and end of every parking episode.

Architecture 4: Localized/Wide-Area Hybrid Transmission

The best system design may be one in which vehicles are equipped with both a wide-area and localized communication technology. Vehicles could be programmed to wait to offload travel information until they pass within range of a roadside reader. If after a specified period (for example, a week) a vehicle has not passed a reader, it could transmit travel data via wide-area connection.

A hybrid system would solve the system reliability and enforcement problems that exist with using solely detection-based communication, as data transmission would default to the wide-area connection if needed. Such a system would enjoy the flexibility of a wide-area, constantly online data transmission architecture. Perhaps most importantly, a hybrid system could reduce operating costs compared to a wide-area, constantly online architecture by itself. Because most vehicles would likely pass within a reader at some point during an uploading timeframe, the cheaper-to-operate localized data transmission technology could shoulder a large portion of data transmission. Moreover, because the wide-area, constantly online technology provides an assurance that data upload will occur, the network of roadside readers may not need to be as extensive; the ability to construct a leaner network of roadside readers could drive down infrastructure costs, compared to a stand-alone localized, detection-based architecture. Finally, a hybrid architecture would enable the fullest menu of value-added applications.

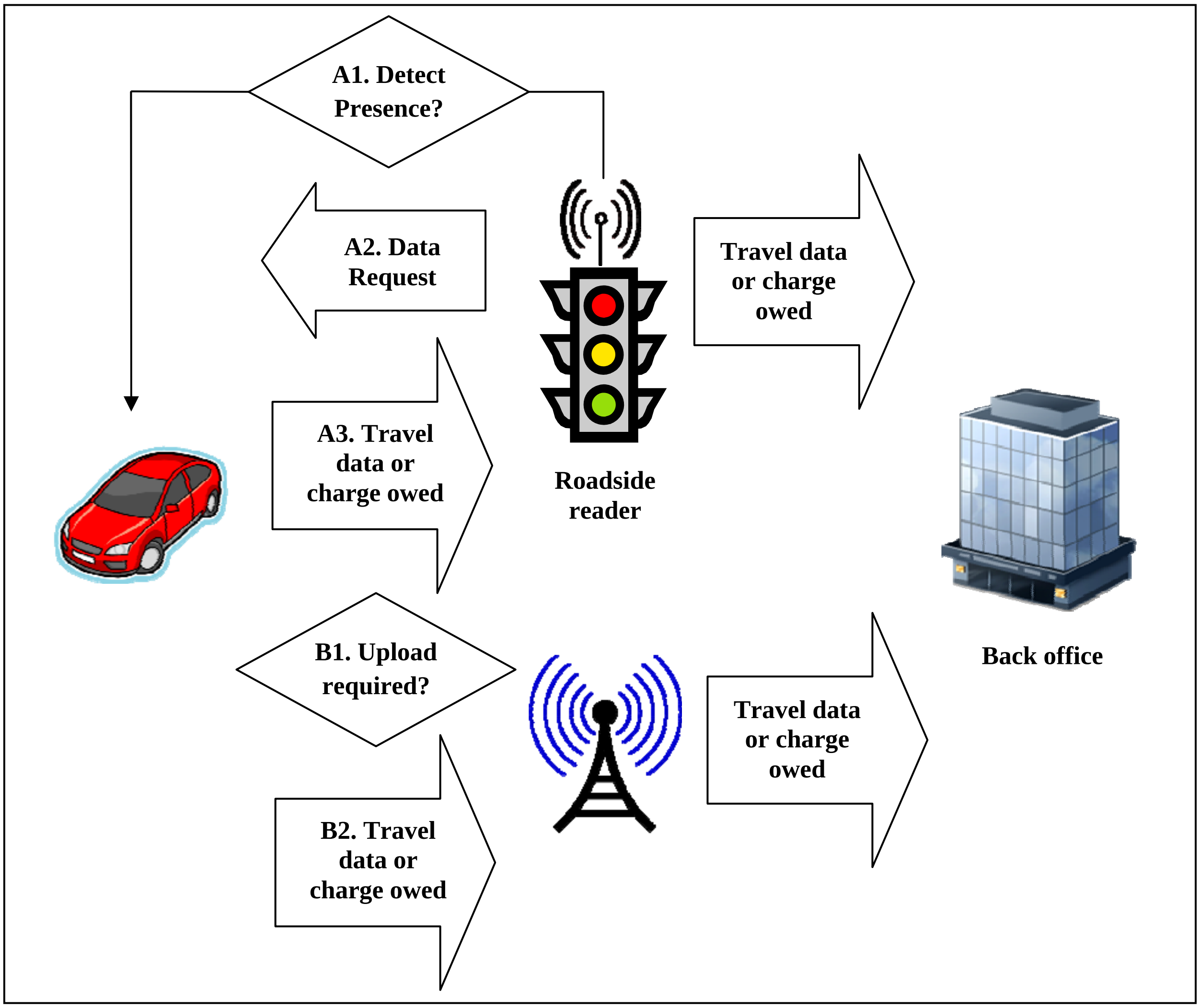

Figure 12: System Architecture Utilizing Localized/Wide-Area Hybrid Transmission

NOTE: Unit health signals not shown; these would be transmitted as in the two base architectures.

Table 5 summarizes the performance of various architectures in key policy dimensions.

Table 5: Comparison of Vehicle-to-Back-Office Communication Logical Architecture Options

Logical Architecture	Manual Reading	Localized, Detection-Based Data Transmission	Wide-Area, Constantly Online Data Transmission	Localized/Wide-Area Hybrid Data Transmission
Suitable Data Offload Technologies	N/A	DSRC, Wi-Fi, Zigbee	GSM	DSRC, Wi-Fi, Zigbee, & GSM
System Reliability	Low/Moderate	Low/Moderate	High	High
User Privacy	High	High/Moderate	Moderate	Low
Data Security	High	Moderate	Low/Moderate	Low/Moderate
System Flexibility	High	Low	High	High
Enforcement	High	Low/Moderate	High	High
Operating Reliability	Low	Low	Moderate	High
Infrastructure Costs	Low	High	Low	Moderate/High
Operating Costs	Low/Moderate	Moderate	High	Moderate/High
Value-Added Options[13]	None	Safety, Traveler Information	Mobility, Parking Finding	All

Data Upload Needs

The temporal frequency with which vehicles should be required to upload travel information or an amount owed from the vehicle to a billing office is a key operational question. The needs of system operators are key in formulating this answer. Determining the optimal data uploading frequency requires balancing the payment requirements of various operators and service providers (toll authorities, parking providers, and insurance companies that may use the system as a platform) with the cost of uploading data. With wide-area, constantly online transmission, more data uploads mean a higher operating cost. In a system with localized, detection-based communication technology, more uploads do not directly increase operating costs but may require higher bandwidth readers, which would drive up infrastructure costs.

A weekly uploading frequency may best balance the competing concerns surrounding data transmission frequency. While the mileage-based user fee itself may be billed on a less frequent basis (e.g., monthly), providers of value-added services, such as tolling operators or insurance companies, may in fact be the major drivers behind data uploading frequency, depending on how often they require payment. Less frequent upload means that if a transmission fails, more data are lost; however, the system can be designed with redundancy (e.g., a previous month's worth of data backed up on board the vehicles) to minimize this risk. A final consideration is that the system should be able to support on-demand data upload. Some special-needs vehicle operators (taxi drivers, delivery drivers) may require the ability to pay daily for bookkeeping purposes. On-demand data upload abilities are also needed for vehicles to communicate unit health signals to the back office if an OBU malfunctions.

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[13] The following value-added applications could be supported by either localized or wide-area vehicle-to-back-office communication: pay-as-you-drive (PAYD) insurance, emissions-reduction discounts, off-peak driving discounts, and congestion pricing (though not congestion pricing involving real-time pricing); these applications have different roadway use assessment requirements.

Payment

There are four major payment options, though in the end the need to accommodate different cohorts of users may require offering multiple payment options.

Payment at the pump is an option that could capitalize on the familiarity of refueling events. This option would likely be employed using a localized data transmission technology with a reader affixed to a gas pump. The reader would download travel information (or amount owed) from the vehicle and then add the amount owed into the driver's bill for gasoline. The fact that payment happens at the time of gas purchase would make it easy to credit back the gas tax to drivers during a phase-in period. Drivers could use the form of payment of their choice (cash, check, or credit card). This payment method has a built-in enforcement mechanism because if users evade payment of the mileage fee in some way, they would default back to the gas tax. Perhaps most importantly, payment at the pump would be in many ways a seamless transition. Drivers would continue to pay for their share of transportation costs during refueling, as they do with the gas tax. However, there are drawbacks to this approach. The cost of outfitting every gas pump in the state with readers could be high. The operation and maintenance of the readers would be an additional burden on either gas stations or the state. Moreover, adding the mileage fee into drivers' gas bills would require the ability to access gas station's point-of-sale (POS) software, and it is not clear if all gasoline vendors would grant this access. Finally, payment at the pump does not accommodate non-gasoline vehicles and thus does not align with the goal of preparing for alternative fuel vehicles touted as a central objective of mileage-based fees.

Monthly billing is a payment option that would enforce the "driving as a utility" message that a user fee is intended to convey. This payment option could work with any architecture and data transmission technology. Travel data or amount owed would be processed by a back office on a monthly basis to generate a billing statement that would then be mailed or e-mailed to users. This option requires a more involved back office than other payment options, as the office would be responsible for not just generating bills but also printing and mailing them out. A perception exists that a more involved back office would lead to the creation of a clumsy bureaucratic agency. However, many users might prefer to get billing statements via e-mail. One major drawback to this approach might be the public's reticence to receive one more bill in the mail each month. Furthermore, the cost of printing and mailing thousands (or millions) of billing statements could be quite high. This approach could engender an enforcement problem if people ignore or do not receive monthly billing statements. Finally, this approach would make crediting back the gas tax difficult during a phase-in period. It would be difficult to know drivers' exact fuel usage. At best, this could be estimated based on their mileage driven and the reported fuel economy of the vehicle (though estimated and actual fuel usage can vary greatly).

Associating payment with vehicle inspections or registration is a third possible approach to payment. This approach would certainly make sense with an odometer-reading-based system. If an OBU that communicates with a back office is used, vehicle inspection and/or registration outlets would need the ability to communicate with the back office, though such lines of communication should not be difficult to establish. Also, payment with registration/inspection would reduce billing statements significantly compared to monthly payment, and a constant revenue stream would be ensured because vehicle registrations and inspections take place throughout the year. Furthermore, this payment strategy provides a built-in enforcement mechanism because drivers could be denied their registration or inspection approval if they do not pay their bill, making it illegal for them to drive. A drawback of this approach is that collecting payment only once a year reduces the salience of the user-fee message (drivers may forget that they will pay at the end of the year for the amount of driving they do). Users may find the cost of payment all at once to be too high. Finally, this payment method would place an additional burden on the Department of Motor Vehicles and state vehicle inspection outlets.

A final payment option is the use of an *online travel account*. This option would function much the same as monthly billing statements, except users could be afforded a greater degree of flexibility as to when they pay. Users could deposit money into the account when convenient or even set up links with bank accounts so that deposits happen automatically. Furthermore, depending on the amount of data allowed off board the vehicle by the system architecture, the account could permit users to view their travel history, making it easy for them to verify that they have been charged correctly and optimize their own driving behavior. An advantage of this approach is that it greatly reduces the costs of printing and mailing bills and the potential enforcement problems that come with monthly statements. Users may, in fact, enjoy the simplicity of automatic online payment in place of another bill in the mail. A drawback of this approach is its inability to accommodate payment by cash or non-computer owners. Many less technologically inclined users may not be comfortable with the idea of online billing. It may be necessary to retain a monthly billing statement option alongside travel accounts in the short term.

Enforcement

Enforcement will be required if users tamper with an on-board unit or fail to pay. A sound enforcement strategy will require a way of obtaining information that there is a problem with a driver and conveying this information to authorities within a timeframe deemed to be sufficiently expedient. Much of the work of enforcement can actually be done preemptively by envisioning the various ways that on-board units could be tampered with and designing against these.

Three general enforcement strategies can be envisioned. The first strategy is to use a form of enforcement that is *built into the means of payment*. Both payment at the time of vehicle registration and payment at the pump provide this. With payment tied in with registration, vehicles can be denied their registration if they do not pay, and responsibility falls on the police to perform their normal duty of finding drivers with expired registrations. In a payment-at-the-pump scheme, no incentive exists for users to avoid payment of the mileage-based fee because they will simply pay the gas tax. There may be issues with each of these payment strategies, however, that preclude their use (see Payment section).

Mobile enforcement is another option. In this scheme, enforcement responsibility would fall on designated law enforcement entities that would be notified by the system back office that a particular vehicle is in violation. Mobile enforcement would be easiest with the deployment of a vehicle-to-back-office data transmission technology that is constantly online and accessible to enforcement authorities, as vehicles without a properly installed OBU could be automatically identified. These authorities could then find vehicles by indentifying their license plate numbers. Mobile enforcement is also an option with localized, detection-based data transmission. OBUs could be programmed to send a signal via vehicle-to-vehicle communication in the event of tampering, and that signal could be picked up by mobile enforcement vehicles. The use of mobile enforcement places an additional burden on police departments but may be more acceptable to the public.

Automatic number plate recognition (ANPR) is a final enforcement option. In this option, roadside cameras are set up to scan license plate numbers. Cameras would be used to catch users in the act of driving with an expired bill or malfunctioning OBU. ANPR technology is becoming increasingly reliable;

however, ANPR cameras require the installation of roadside infrastructure that must be built, maintained, and guarded against vandalism. Furthermore, there are significant public acceptability issues with the use of cameras in Texas.

On-Board Unit Issues

Placing on-board units in vehicles raises a few important questions. One major issue is the choice between allowing aftermarket devices and requiring devices by original equipment manufacturers (OEMs). The past few years have seen a proliferation of aftermarket devices with GPS that users install in their vehicles or routinely carry on board. The increasing presence of personal navigation devices and cellular phones with positioning abilities makes the use of these devices as a mileage-based user fee technology a very real possibility.

The aftermarket device approach could best be described as treating the mileage-based user fee as one of many applications supported by the device. There are a number of advantages to the use of aftermarket devices. For instance, using aftermarket devices could bring the cost of on-board units down significantly by piggybacking onto the functionality of devices for which users have proven a market exists. Aftermarket devices could enable greater customization as users could select the device that supports applications of their choice in addition to the mileage-based user fee application. Customizability might make users more inclined to buy devices initially, which could speed adoption of a mileage-based user fee program. Using aftermarket devices also shifts the burden of hardware upgrades to users. There is a very real possibility of a rapid succession of generations of on-board units in the early years of a mileage-based user fee program as device manufacturers develop new applications and capabilities. During these initial years of growth, users may indeed desire the flexibility to replace their on-board unit with newer, more capable units.

Perhaps most importantly, using aftermarket devices ensures that already-manufactured vehicles can participate in a mileage-based user fee program. This is extremely important given the slow rate of vehicle turnover (15-20 years) in the U.S. While there may be chances to retrofit existing vehicles, the use of aftermarket devices would have much the same effect without necessarily requiring users to bring their vehicles in for the retrofit.

Aftermarket navigation devices thus seem the best route to garner participants in a mileage-based user fee program in the short and medium term. However, in the long term, when OBU technology and application offerings have stabilized, there are advantages to requiring that on-board units be installed by OEMs. While it may be possible to shift many drivers by using aftermarket devices, some drivers may not ever buy an aftermarket device on their own. Achieving a total transition away from the gas tax will likely ultimately require building devices into vehicles. There may be a further benefit to legislating an ultimate date by which new vehicles will be required to be capable of being assessed a mileage-based user fee. Legislating this date with some foresight would ensure a long-term place for mileage-based user fees, thereby removing the risk of investing in the research and development of supportive technologies and auxiliary applications.

Installation needs are another important issue. OBUs could be designed to require a certified installation or be designed for self-installation. OBUs that connect to the vehicle's diagnostic port will likely require certified installation, while those using only GPS to measure distance could conceivably be self-installed. A self-installed device could either be mounted on the vehicle's dashboard or windshield or built into a portable electronic device, such as a cellular phone, that the user otherwise carries.

The choice between certified and self-installation is to some degree a tradeoff between cost and security against tampering, vandalism, and theft. Certified installations could constitute a significant startup cost but would likely result in a device that is more difficult to access and more permanently affixed to the vehicle. On the other hand, self-installed devices do not necessarily need to be highly tamper-proof, as these devices could be programmed to send unit health signals back to a central office in the event of tampering. A self-installed device would thus likely require a data transmission technology that is always connected to the back office, such as a cellular-based technology, so that authorities could be immediately notified when a unit is not properly installed. While enabling this constant connection with the back office is a significant technical requirement, there may be other reasons why it is desirable to design a system this way (e.g., for many value-added services). In a system design where the vehicle is already always connected, the marginal cost of enabling unit health signals would be low.

Opportunities exist to employ the capabilities of the numerous aftermarket devices that consumers already have on board to bring down the costs of installing on-board units in vehicles. One risk with using some aftermarket devices that are not permanently affixed to the vehicle, such as cellular phones, would be the risk of a driver forgetting to bring the device on board. The best way to avert this issue might be to install a permanent distance-measuring device into the OBD port and use the cellular phone or GPS only for positioning abilities. The OBD port device and navigation device could communicate with each other via a highly localized communication technology such as Bluetooth or Zigbee. The OBD port device would provide backup distance measurement if a user forgets to bring the positioning device on board. Users could be charged an average rate for miles lacking a position stamp (or a slightly above-average rate to penalize users for not having the navigation device).

Value-Added Services

It has been widely recognized that the technology that might be deployed for a mileage-based user fee could support a wide range of other applications and services. There is great interest from prospective providers of these applications and services in the future of mileage-based fees due to their potential profitability. The ability to offer value-added services, moreover, might prove to be a valuable asset in the roll-out of mileage-based user fees.

Goals

The ability to offer value-added services could achieve three goals for Texas. First, value-added services might accelerate phase-in of mileage-based user fees, particularly those that will be administered using an on-board unit. If mileage-based fees are to be revenue neutral compared to the gas tax, there is little incentive for users to make a switch. This is especially true if users are required to purchase an on-board unit for their vehicles. The presence of value-added services, however, might incentivize early adopters. Second, value-added services would increase the perceived functionality of a mileage-based user fee system. This is especially pertinent because it is likely that in the short term, administrative costs for a mileage-based user fee will be higher than the gas tax. The public may be willing to accept higher administrative costs if it perceives the mileage-based fee as also supporting other valuable services. Finally, there are chances to include some revenue generating bundled applications with the mileage-based fee. Tolling, parking, and insurance applications might all be supported by the same on-board unit and could help to spread the costs of operating the system more thinly.

Examples of Value-Added Services

Numerous types of value-added services have been proposed. *Safety* applications are a major service that might be provided by OBU manufacturers or vehicle manufacturers to increase the value of their products. Alternatively, the government might support safety applications (though these are not a revenue generator) due to the social benefits. Many of the safety applications discussed are being developed through IntelliDrive (see Integration with VII/IntelliDrive section). Potential safety applications include signal and stop-sign violation warnings, curve speed warnings, collision warning and crash mitigation applications that could warn drivers of impending crashes and even tighten seatbelts or deploy airbags *before* impact, road and travel condition warnings, and gap judgment assistance applications for unprotected left turns. Many safety applications will require the vehicle to communicate with surrounding infrastructure and with other vehicles. These applications are thus best suited to localized data transmission technologies such as DSRC, Zigbee, or Wi-Fi.

Applications to improve *mobility* have also been widely discussed. Localities and urban regions could use the same platform that a mileage-based user fee operates from to support tolling of facilities, cordons, or system-wide congestion pricing. A variety of roadway pricing schemes could be envisioned including a hierarchy of roadway segment rates, special rates for peak-hour driving, or dynamic pricing in which the cost of entering and driving on a particular facility varies with the current congestion level of that facility. The rate an individual vehicle is charged could be allowed to vary based on vehicle characteristics (to reward or penalize vehicles based on environmental impacts) and/or household income (to ensure system equity). Individual vehicles could be used as probe vehicles to measure travel times and relay information to all drivers in the system. Also, individual vehicles could obtain real-time routing assistance (which could give least-cost or least-time route) based on this information. One caveat is that more complex mobility programs may require system architectures that allow more travel information off board the vehicle and in which the vehicle is always in touch with the back office. This may necessitate a thick-client or anonymous loop-back proxy architecture and cellular-based data transmission technology. To ease privacy concerns, many mobility programs could be designed in such a way that they are opt-in. Tolling and congestion pricing applications could help to offset some of the system costs because these are revenue generators.

Localities and urban regions also might benefit from the ability of a mileage-based user fee system to support *transportation planning studies*. Information could be purchased from drivers to support household travel surveys or facility performance studies.

Mileage-based user fee on-board units could also support various *parking* applications. Parking-location applications could save drivers time in finding parking spots in downtown urban areas. More expedient parking would also reduce cruising, which has a detrimental effect on traffic circulation and is a significant source of emissions. Parking payment could also be conducted through on-board units, saving users time and reducing costs for lot managers. Parking locators require that the OBU dial in at the beginning and end of each parking episode to support management of the supply of spaces and thus will likely need a cellular connection. Parking applications are likely another revenue generator.

Pay-as-you-drive insurance is a value-added service that could benefit society by incentivizing reduced driving. PAYD insurance rectifies the economically inefficient situation that currently exists in which drivers within the same class pay the same amount for insurance coverage despite the fact that crash probability is higher for drivers who drive more. Insurance companies can use more detailed information on drivers' behavior, including how much they have driven, which roadways and times of day they have driven, and the severity of their acceleration and braking, to more accurately assess their risk. For most drivers, this enables insurance companies to charge them a lower premium (when previously they had overcharged to ensure they would cover their costs). PAYD insurance requires a great amount of drivers' travel information to leave the vehicle; however, given the potential savings (a Brookings Institution study estimated that nationally two-thirds of households would save under PAYD insurance with an average savings of $270 per car), many drivers may consent to this release.[14] PAYD insurance could be supported by any data transmission technology and could be a revenue generator.

Finally, travel information collected from a mileage-based user fee system could be used to support *driving behavior incentives* including emissions rewards, off-peak driving discounts, and generalized routing assistance. These incentives could be offered by cities and metropolitan planning organizations (MPOs) to assist in reducing congestion and complying with federal air quality requirements. The chance to earn these incentives would likely be available on an opt-in basis, as these would require individuals to release detailed travel information from the vehicle.

System Architecture Needs

Previous sections discussed how various stages of the system architecture can facilitate or inhibit the provision of value-added applications and services. The actual ability to provide value-added services depends on the sum of those stages. This section looks at the complete logical requirements for a wide range of value-added applications. The following is a general outline of the logical requirements for different value-added services (Table 6). Specific architecture needs will depend on the specific deployment scenario. For instance, in general, in-vehicle signage can be provided with only a location-stamp. If a city wanted to provide in-vehicle signs for school zones during drop-off and pick-up hours only, however, then time-stamps might also be required. Similarly, a cordon toll could be levied with only location-stamps, but if the cordon toll is to be in effect only during certain hours of the day, then time-stamps must also be collected. In addition, there may be innovative designs that are able to facilitate some of these services with fewer requirements than outlined here.

Tolling Industry Perspectives

Representatives of the tolling industry interviewed and present at the Mileage-based User Fee Symposium voiced a general interest in mileage-based user fees. These representatives cautioned, however, that the tolling industry's interest might be limited to using on-board units for its own purposes and that they would want to retain control of their own money and operations. Value-added services were of considerable interest to tolling representatives. One representative noted that the tolling industry might develop value-added capabilities, though it may need to engage third-party applicants to do so. The appeal of bundled services to the tolling industry has two aspects. First, it is expensive for the tolling industry to get devices into vehicles, and value-added services could make these more attractive. Second, value-added services might provide a way for the tolling industry to make its routes more attractive by offering services not available on free routes. Overall, though, the tolling industry representatives seemed to view mileage-based user fees as a potential auxiliary application on a device that they would provide and/or manage.

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[14] Bordoff, J.E., and P.J. Noel, "Pay-As-You-Drive Auto Insurance: A Simple Way to Reduce Driving-Related Harms and Increase Equity," The Brookings Institution: The Hamilton Project. Discussion Paper 2008-09. July 2008.

Table 6: System Architecture Needs of Different Value-Added Applications and Services

Value-Added Application	Data Collected		Data Leaving Vehicle		Data Transmission Capability			Minimum Data Upload Frequency			Revenue Generator
	Location Stamp	Time Stamp	Location Stamp	Time Stamp	Localized, Detection-Based	Wide-Area, Constantly Online	Vehicle-to-Vehicle Communication	Monthly/Weekly	Daily/Hourly	Real-Time	
Safety											
In-vehicle signage	✓				✓					✓	
Crash avoidance					✓		✓			✓	
Gap judgment aids					✓		✓			✓	
Mobility											
Routing assistance	✓	✓	✓	✓	✓	✓				✓	
Real-time traffic data collection	✓	✓	✓	✓		✓				✓	
Roadway Pricing											
Facility-based tolls	✓	✓	✓	✓	✓	✓			✓		✓
Lane-based tolls	✓	✓	✓	✓	✓	✓			✓		✓
Peak-hour tolls		✓		✓	✓	✓			✓		✓
Cordon tolls	✓	✓	✓	✓	✓	✓			✓		✓
Dynamic pricing	✓	✓	✓	✓		✓				✓	✓
Transportation Planning											
Household travel surveys	✓	✓	✓	✓		✓		✓			
Speed studies	✓	✓	✓	✓		✓		✓			
Parking											
Parking location	✓	✓	✓	✓		✓				✓	✓
Parking payment	✓	✓	✓	✓		✓				✓	✓
Pay-as-you-drive Insurance	✓	✓	✓	✓	✓	✓		✓			✓
Driving Behavior Incentives											
Ecodriving rewards	✓	✓	✓	✓	✓	✓		✓			
Off-peak driving rewards	✓	✓	✓	✓	✓	✓		✓			

Integration with VII/IntelliDrive

A U.S. Department of Transportation initiative called IntelliDrive (previously known as Vehicle Infrastructure Integration [VII]) would use technology similar to a mileage-based user fee. IntelliDrive is “a suite of technologies and applications that use wireless connectivity with and between vehicles, between vehicles and the roadway, and with devices (such as consumer electronics) in the vehicle to achieve transformational safety, mobility and environmental improvements."[15] Two major ongoing thrusts of IntelliDrive research and development include safety applications that deliver instantaneous hazard warnings using DSRC and mobility applications that mine real-time travel data using software downloaded to drivers' GPS-equipped cellular phones.

IntelliDrive is still in the development phase, and the timeline and nature of an eventual deployment are unclear. IntelliDrive may not be a suitable platform for a statewide system because IntelliDrive applications are oriented toward urban areas. In the long term, however, opportunities may exist to use IntelliDrive infrastructure as one of the avenues for data upload from vehicles in urban areas. IntelliDrive might also be used by local agencies to levy additional road user fees on specific facilities to augment a baseline state mileage-based fee.

Two Differing Views of the Privacy Question

While consensus exists that privacy is a significant barrier to public acceptability, there is not yet agreement on how to approach the public on the topic. Indeed, discussion at the symposium and interviews with stakeholders revealed two different lines of thinking regarding privacy. The first strain holds that the public should be guaranteed absolute privacy protection. No information other than an amount owed should be permitted to leave the vehicle. According to this view, all charge computation (whether for a mileage-based user fee or any other application) must happen on board the vehicle, ruling out numerous system architectures. One interviewee made the point that while it is true that individuals have already disclosed as much or more private information as would be needed to administer a mileage-based user fee system to other entities, the public would likely not buy this explanation. This interviewee stated that the European Union (EU) was already moving in the direction of legislating that all mileage-based user fee systems keep all user travel information on board the vehicle.

A competing position regarding privacy held that there are already precedents for how industry should handle consumers' sensitive information. An emerging mileage-based user fee industry would adopt the same procedures and safeguards already established by industries such as the banking and insurance industries. According to this line of thinking, there is no need to legislate limits on what information can leave vehicles because the first adopters of a mileage-based user fee system will demonstrate to the rest of the public that there is no need to fear being tracked or watched. The interviewee who voiced this opinion argued that if handlers of sensitive information maintain a detailed trail of who has accessed information and what changes have been made, then users' privacy can be adequately protected.

Ultimately, the question of whether to legislate a baseline level of system privacy or whether to allow industry to demonstrate its ability to protect privacy is a question for policymakers.

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[15] http://www.intellidriveusa.org/about/faqs.php

What's Next: Recommendations for Texas

Before developing a mileage-based user fee concept of operations and pilot projects, the following key policy questions should be considered.

1) Are congestion management, local revenue retention, and the provision of value-added services primary goals? If these are central objectives, then Texas will need to design a mileage-based user fee system that collects data on not just *how much* users have driven, but also *where* they have driven. A system of this sort will be more complex and entail a higher public education burden. Local revenue retention is an interesting objective to consider, as it was one of the major points of attraction in public acceptability research. Focus group participants, especially those from smaller rural localities, liked the idea that reallocation of transportation funds could be based on an actual record of where road use has happened rather than a political process. These Texans perceive their roads as heavily used by external drivers who pass through their localities but also feel outmuscled for funding by larger metropolitan areas. Achieving the goal of local revenue retention means that the system will almost certainly require vehicles to be equipped with on-board units with GPS. If MBUFs are sought simply to prevent the erosion of fuel tax revenues, however, annual odometer readings may suffice.

2) Does Texas want to pursue a two-track system? The idea of a system with a low-tech and high-tech track is attractive from many standpoints. Users could opt for an odometer reading or an on-board unit that features different value-added services. Those users participating in the odometer reading would pay for all miles, while those users with an on-board unit could be credited back miles driven on non-taxable roads (e.g., out-of-state roads or private farm roads), further incentivizing participation in the high-tech track. A low-tech track could be quickly established and begin to develop public familiarity with the concept of mileage-based charging. A low-tech track could be pilot tested and/or established even before a high-tech track is ready. Initial participants in the high-tech track could demonstrate the system's ability to protect privacy, fairly and accurately assess charges, etc. The establishment of a market of on-board users could pull the development of new bundled features and applications. However, a system of this type raises a fairness question: Is it fair to require users to participate in the high-tech track in order to avoid being charged for miles driven on non-taxable roadways?

3) Will Texas legislate limits on what information is permitted to leave vehicles? This would be a bold step that could go a long way toward easing privacy invasion fears. The EU has prohibited any location information whatsoever from leaving the vehicle. In other words, on-board units will have to perform all of the charge computation on board. The vehicle's on-board unit will have to store a rate schedule, compute an amount owed that is sent back to a billing office, and store the travel history so users can verify their bill. On the other hand, many participants in interviews with tolling, telecommunications, and computer hardware industries did not see the need for such limits. In the judgment of these participants, drivers' sensitive information could be handled using safeguards similar to those used by the financial and insurance industries.

It is worth noting that limiting what information can leave the vehicle impinges greatly on many value-added services that require knowledge of where the vehicle is. Limiting what information can leave the vehicle would also require an initial degree of trust from users in the computation of their bills. In other words, users would only get a detailed breakdown of how their bill was computed in the event that they disputed the amount owed and authorized the provider to access their stored travel history from the vehicle and show them the breakdown. Customers generally trust utility companies to accurately meter their electricity and water usage. Cellular phone bills, though, typically come with a full record of calls attached to them.

There may be less extreme options: Texas could legislate that detailed travel information is allowed to leave the vehicle only if a driver waives their “right to travel privacy.” Alternatively, Texas could legislate that travel information is allowed to leave the vehicle if it is stripped of some level of specificity. For instance, travel information could be aggregated by roadway type or time of day, which would permit providers to furnish drivers with a more detailed bill. Ultimately, though, Texas must first decide whether it wants to move to legislatively guarantee the privacy of certain travel information or leave it to the private sector to demonstrate its ability to protect user privacy.

4) Will new infrastructure be built? Will infrastructure built be publically or privately owned, operated, and maintained? Will on-board units be public property, user property, or private provider property? A number of architectures can be immediately eliminated if there is no willingness to construct new infrastructure. Similarly, many architectures likely signal private ownership and operation of infrastructure (e.g., the use of wide-area communications like GSM). Aside from the fact that many architectures implicitly assume public or private ownership, it is difficult to discuss cost in any detail until basic ownership and responsibility questions are decided.

5) Will Texas pursue existing technology options or incubate next-generation technological solutions? Odometer readings could be implemented today with an agreement with state inspection outlets and a contract to invoice drivers. The technology for a system consisting of GPS-equipped on-board units that communicate with a central office is theoretically available today. The major communications technology being discussed today—cellular communications—is, however, cost prohibitive. With cellular communications, every data transmission is essentially a phone call. At the low end, operating costs of \$5 per vehicle per month are being quoted. The gas tax costs about \$0.20 per vehicle per month to administer, so costs this high will likely be seen as burdensome. One option is to pursue cellular-based on-board units and bundle enough services in the unit that users perceive \$5 per month worth of value. Bundling other revenue-raising applications such as parking payment, pay-as-you-drive insurance, and tolling applications in the on-board units could help to spread costs thinner.

Another path toward a cost-effective system might involve combining cellular communications with another communications technology that is cheaper to operate. Most other communications technologies require some sort of roadside physical infrastructure. Because it is likely cost prohibitive to achieve statewide coverage of roadside infrastructure, it would seem that an MBUF system in Texas will need cellular-equipped OBUs. There are intriguing opportunities to reduce operating costs significantly by coupling cellular communications with a second communications technology. Other communications technologies (DSRC, Wi-Fi, Zigbee, etc.) operate in a more localized manner and are essentially free to operate. Data transmissions through these technologies are more similar to a file download than a phone call. There may be chances to strategically place readers in urban areas near frequently traversed roadways. OBUs would be programmed to wait to upload data until they pass near a reader but to send data via cellular connection if a reader has not been passed within a specified period. While much discussion of localized communications technologies has focused on smaller readers that are placed all along roadways, one could design high-capacity readers that would be placed near freeway intersections. Strategically placed high-capacity readers could capture significant numbers of drivers and reduce maintenance burdens.

In the long run, developing these optimizations could be a better way to bring system operating costs down to a reasonable level. Quite simply, it might be a safer option to develop a cheaper system than to pursue a more expensive system and count on users to perceive it as valuable enough.

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