CHAPTER 3

Technology Options for Charging

3.1 Background

Historically, tolling via cash at discrete locations on the route had been the only direct means of paying for road use. The traditional policy of using tolls to help pay back the cost of construction and operations has since been supplemented by several new forms, including area pricing, cordon pricing, and distance-related charging, largely for demand management purpose. Technology availability and capability helps influence policies, and vice versa: Policy development guides future direction of technology evolution. This chapter focuses on the collection of charges for road usage based on measurement of road usage, and the capture of vehicle-related information to support the enforcement process when a charge cannot be properly levied. For charging to be effective, it cannot depend on every vehicle being equipped with technology. If the use of an OBU is not mandatory, then the occasional user that does not have an OBU needs to be included, and alternative payment methods need to be offered, including cash.

Perhaps the first notable study of charging technologies was the Smeed Report [1] published in 1964, which examined the economic and technical issues associated with road user charging as a restraining and demand management measure. In the context of congestion charging, the report made the following observations.

> Vehicles must carry identification units which enable their presence to be recorded by roadside apparatus. The recording must be in a suitable form to comprise the input data of the computing equipment. The system must be capable of distinguishing between, say, 30 million different vehicle identities [. . .] We have enquired about optical, electromagnetic, radar and sonic methods, and the only serious proposal put to us was the electromagnetic Link Tracer suggested by Professor William Vickrey for vehicle identification in Washington DC. The capital cost quoted for the vehicle, roadside and computing equipment was £12 10s 0d per vehicle [. . .] a good deal higher than the £5 that we allowed. [Note: £5 in 1964 is about £64 ($112) today.]

A suggested alternative scenario was based on time spent within a priced zone. Vehicles would be required to install an automatic meter.

> The automatic meter tries to eliminate much of [the responsibility of both driver and traffic authority] by placing control apparatus in the road [. . .]. The setting of the meter is performed for [the driver] by [a] switching circuit which operates in response to signals received for road-sited transmitters installed at the zone entry and exit points and intermediate points within the zone.

The technologies available when the report was written to implement charging systems were severely restricted to electromechanical devices, with almost no communications capabilities available the time. Nevertheless, the principles of vehicle identification, location-specific charging, and automatic metering within charged zones described over 40 years ago underpin today's policy approaches to charging. Building on Chapter 2, which translated policy options into functional requirements, the following sections map these onto feasible technologies, and present the pros and cons of the options available.

For the 10 years beginning with 1987, the majority of pay-per-use charging services were based on ETC plazas. Whenever the vehicle enters the toll lane, the vehicle's OBU is accessed to identify the means of payment and other account-related information, in a process known as AAI. AAI provided a simple solution for locally focused charging schemes that are based on the pay-per-use policy, although some of the earliest projects offered subscription accounts. Trondheim, one of Europe's first ETC installations, also applied a maximum fee payable in any month. After opening an account, the user installed a small OBU on the inside of the vehicle's windshield. An example of an OBU design is shown in Figure 3.1.

The use of the term *tolls* reflects the underlying rationale for funding of the infrastructure and its operation, in principle, although any automated process that enables the measurement and charging of road usage for the same purpose can also be described as an ETC. Chapter 2 distinguishes between the policy objectives of tolling and road user charging, and this distinction is continued here to show how charging policies influence the selection of charging technologies, and how these technologies, in turn, must be combined to meet policy requirements.

Chapter 2 also identified a range of possible charging policies, including tolling and other forms of pricing based on crossing cordons, traveling within a charged

Figure 3.1 Typical DSRC OBU.

area, and variations of these policies. Charging can also be applied to all road users in selected geographic areas, such as an interurban highway or a city. Furthermore, vehicles may be charged only if the entry to the charged area is within a specific time period. The technologies required in the vehicle and roadside infrastructures have become more complex as the charging policies have evolved. Conversely, in many cases, the technical possibilities have often led to the consideration of new policy options.

Section 3.2 defines the minimum operational requirements for charging for road use, and Section 3.3 highlights how precedence can influence scheme designs. The dilemma is whether or not to allow a progressive evolution to more advanced forms of charging, since this approach may encourage organizational and institutional inertia, limit policy innovation, and reduce the long-term benefits that tolling and road user charging could offer. The alternative is more rapid change as technology capability permits.

Automating the charging process means that payment is no longer linked to charging. Section 3.4 explains why this is the case and what this means for future charging schemes. Since the choice of technologies is guided by the underlying charging policy, Section 3.5 identifies technology building blocks (e.g., traditional plaza-based ETC schemes, and advanced city-wide, regional, or national pricing schemes), and shows how these technologies can be combined to deliver various charging policies. This section also shows how scheme operators can accommodate all road users, even those without any in-vehicle technology. Section 3.6 introduces standardization and the different levels of interoperability that enable road users to travel within a charged road network made up of different schemes, each with their own charging policy. The evolution to increasingly more complex charging policies places more diverse demands on the charging technologies themselves. Section 3.7 focuses on how the technology building blocks will evolve, and how closer integration with the vehicle may be required to improve the efficiency and effectiveness of the charging and enforcement processes. Finally, Section 3.8 summarizes this chapter.

3.2 Minimum Operational Requirements for Charging Technologies

The use of tolling and road user charging has increased as an efficient means of funding infrastructure development, operation, maintenance, and demand management, both in the urban environment and increasingly on strategic arterial routes. Today, a road user, whether in a developed or a developing country, is more likely than ever to come into contact with such a scheme. In regions where toll collection is already widespread, a typical journey may include traveling on two or more separately charged road segments or zones.

Each scheme operator is likely to be presented with a bewildering array of technology options for charging and enforcement. Although the imposition of tolls or charges is enabled by technology, the charging policies have been shaped by technologies themselves. Policymakers need to know that the policy can be delivered at an acceptable risk. In turn, the requirements on charging technologies are indirectly determined by the charging policies themselves.

The starting point to identify charging technologies is the set of minimum operational objectives that need to be met by a charging scheme:

- To uniquely identify the vehicle, since it is the vehicle's use of the road that is chargeable;
- To measure road usage, either as discrete events or on a more continuous basis, to determine the correct charge;
- To uniquely identify an authorized means of payment;
- To inform the driver or account holder that a charge has been levied, either at the point of charging or via a periodic statement;
- To support the enforcement process, ensuring payment if a vehicle cannot be linked to an authorized means of payment, or if other charging discrepancies exist.

Many of the products and services that are required to successfully implement a charging scheme depend on technical innovation, technology development, and deployment. The user requires that the service must be fair, understandable, easy to use, safe to use while driving, and convenient. Developing user confidence, accessibility, and a high level of compliance are all critical to the long-term economic success of a charging scheme.

In-vehicle equipment must communicate the vehicle's road usage and other declarations (e.g., exemptions, discounts, or user-related information) to external systems. For example, an AAI system only needs to know the account information at the point of vehicle detection, whereas a distance-related charging scheme needs to know the distance traveled on chargeable roads. If there is no in-vehicle equipment, then the enforcement process needs to be based on the only unique information that can be observed on the vehicle, namely, its license plate. Chapter 4 elaborates on the relationship between charging and enforcement.

3.3 The Dilemma of Precedence

Technology selection is not an automatic process. Existing technology is often used as an excuse to do more of the same in the future, without consideration of changes that are occurring in the fiscal, political, technical, and legislative processes that are often inextricably linked to charging. Historical precedence provides lessons on what could work, and offers reassurance that a specific technology will meet the requirements where substantial public or private investment is required (e.g., building a new road). This leads to a combination of past and present technologies coexisting in a single scheme, particularly for tolling, where toll plazas allow the simultaneous operation of both drive-through ETC lanes and less automatic forms of payment.

This simultaneous view on what has been shown to work and what will be required for the future often presents a dilemma. In the worst case, operators act independently, resulting in a fragmented approach to technology selection, based entirely on satisfying local needs and minimizing risk. Technology choice should instead reduce the cost and improve the efficiency or effectiveness of the charging process, while meeting policy objectives for tolling and road user charging, and, if possible, enabling new service offerings to road users. However, as road user charging is adopted at local, regional, and national levels, road users will typically travel on several chargeable road segments, each based on a different charging policy. Users should not have to understand the differences between the increasing number of charging schemes, even if the charging technologies are apparently identical. Instead, users should expect to experience seamless roaming between these policy areas, in the way that mobile phones roam between networks and across international boundaries. The complexity of an individual scheme and its relationship to other schemes should therefore be invisible to users.

If each policy area required a different charging technology (e.g., tariff structures, payment channels, and so forth), then the user would face functional and usability barriers that are unrelated to any other costs of paying for road use, which could undermine the user's understanding and support for the principles of charging. The technology choices should be limited, but may be more than one. Technology choice should therefore aim to make road user charging more accessible and understandable for road users. This aim must also consider the privacy and data protection expectations of road users, particularly when there are multiple scheme operators, as discussed in Section 4.4.4.

3.4 Charging Versus Payment

Cash payment of tolls highlights the simplicity of the charging process. Traditional cash-based toll collection systems combine charging and payment into one event, simply by the transfer of cash from the road user to the toll collection attendant at the point of payment.

As automated charging methods are introduced, we need to clearly differentiate between charging and payment. The charging process is strategically important for all scheme operators; it uses all the information relating to the vehicle's passage to establish the amount due. Conversely, payment is the obligation of road users (or accountholders) to transfer funds to the scheme operator, or to an intermediary established to accept fees relating to the road usage.

Road usage and payment for road usage are usually separated in time, at least for electronic payment methods. A driver may either prepay or postpay for road usage. For example, closed toll roads (see Section 2.3.2) depend on the issuance of a ticket (physical or electronic) on entry, which is then used to calculate the fee at exit. The toll road operator requires the user to provide a valid means of payment at the point of exit, which could be an electronic record provided by in-vehicle equipment that contains enough information to uniquely identify an authorized account.

The account itself may be prepaid or postpaid, but nevertheless, the scheme operator would need sufficient confidence (i.e., a financial risk assessment embodied in business rules) to allow the vehicle to leave the chargeable road segment without enforcement. For example, if a barrier-controlled ETC toll lane cannot identify the account information (or if none were provided), then the enforcement barrier would prevent the vehicle from leaving the lane. However, on an open highway, drive-through nonstop toll plaza, or in an urban charging scheme, enforcement would typically be based on digital imaging systems used to capture evidence of a vehicle's identification and presence. The charging and payment processes are inextricably linked to the enforcement process, regardless of the choice of charging technology. Chapter 4 further discusses the relationship between charging and enforcement, while Chapter 6 explains the matching of payments with charges.

The measurement of distance traveled would trigger a payment after the road usage has occurred. The collection of records that enables a charge to be computed may occur hours or days after the recorded road usage, simply to reduce the load on the record collection and billing system. Chapter 6 discusses central system operations and billing in detail.

3.5 Functional Requirements and Technology Choice

3.5.1 Technology Building Blocks

The first step in identifying charging technologies is to determine the functional requirements, and the second is to translate them into technology options.

The apparent choice between technologies is more likely to be a choice between a cluster of complementary technologies that, when coordinated, measure, report, and calculate road usage. The charging policy itself will determine whether it is necessary to measure the distance traveled by the vehicle, or whether it is sufficient to only detect and identify the vehicle once (e.g., on entry to an open toll road). The appropriate technology building blocks sometimes will be obvious due to local precedence. The introduction of ETC at a single isolated plaza requires no more than vehicle (account) identification and notification to the user that a charge has been made. If vehicles are charged for the use of all roads based on distance traveled, then the technology building blocks will need to include distance measurement, reporting, notification to the user, and integration with fixed and mobile enforcement. There are intermediate cases in which the technology options are not clear, but the steps remain the same; policy requirements must be translated into functional requirements, and then the functional requirements used to outline the technology building blocks.

Table 3.1 shows the relationship between functional requirements and technology building blocks. Since a charging policy cannot exist without the means to enforce it, Table 3.1 adds another function—the need to support the enforcement process. Additional technologies are needed to make the charging process secure, robust, accurate, and auditable. A short list of these essential elements is also provided.

There are three main approaches to charging, each comprising a cluster of the technology building blocks:

- DSRC;
- CN/GNSS/DSRC and augments;
- ANPR.

DSRC and GPS have evolved in parallel from very different origins, and both were conceived as tangible technologies in the mid-1970s. Both have passed through

Table 3.1 Functional Requirements and Technology Building Blocks

Function	*Technology Building Blocks*
Vehicle identification	ANPR RFID Dedicated short-range communication (DSRC)
Discrete location determination	ANPR + video image capture RFID DSRC Future methods, such as continuous air interface for long and medium range initiatives (CALM) (multiple communication methods), and ultrawideband (UWB) for localization within discrete zones
Continuous location determination	Satellite-based positioning: GNSS (including GPS, GLONASS, Galileo, and Loran-C) Terrestrial positioning systems, such as Enhanced Observed Time Difference (E-OTD), time of arrival (TOA), angle of arrival (AOA), and their variants/hybrids Proximity and vicinity detection In-vehicle positioning augments and assisted global positioning system (A-GPS) provided by the network
Measurement of distance traveled	Identification of individual segments and addition of their separate lengths Odometer/tachograph Integration of position estimates over time, matched to a map of the road network
Reporting from in-vehicle equipment to enable road usage to be charged	Vehicle-infrastructure communications: Localized discontinuous communications, such as DSRC Cellular networks (CN), such as GSM, code division multiple access (CDMA), wideband CDMA (WCDMA) Future options: Wi-Max Secure memory card or smart card Other methods of reporting, such as manual pay stations
Notification to road user or accountholder	Audible indicator or man-machine interface (MMI) (e.g., display or keypad) Off-line notification by e-mail, short message service (SMS), and so forth
Enforcement support	OBU localization Electronic vehicle identification (EVI), electronic registration identification (ERI) Localized vehicle-to-infrastructure communications, such as via DSRC
Additional essential functions	Integration with enforcement Data encryption and security key schemes to protect charging data from tampering or modification OBU authentication at charge points to protect accounts from fraudulent OBU Vehicle detection and classification to ensure that the correct charge relating to vehicle type is made Application support, such as on-off board map matching, and route reconstruction to help build the final bill for road usage

several generations, both are now available in mass-market products, and both are well supported by an internationally competitive industry. GPS and DSRC perform completely different functions (positioning and communications, respectively), but this has not stopped frequent, direct comparison and misleading claims of the relative split of cost between the vehicle and infrastructure by industry segments that have historical roots (and significant R&D investments) in either GPS-based or DSRC-based developments.

ANPR was initially used in closed user group access control schemes from about 1985. It then provided support to manual enforcement processes for toll plazas from about 1990. It has generally been accepted as an essential enforcement tool for tolling and road user charging applications.

A scheme designer making decisions on charging technology choice will also need to consider the degree of automation influenced by several factors, including the quantity of charging events, vehicles, and accounts. However, the potential quantity of unusual conditions can be the most significant operational cost driver. These exceptions include misread license plates, errors in measured distance, dependency on the user at the time of charging, process errors, and so forth. The main determinants of technology choice include the charging policy, type of road user (measured by frequency of use), capture accuracy (detected events), data capture accuracy (accuracy of reporting events), and the business case for the technology itself. Figure 3.2 shows the relationship between three technology forms differentiated by usage.

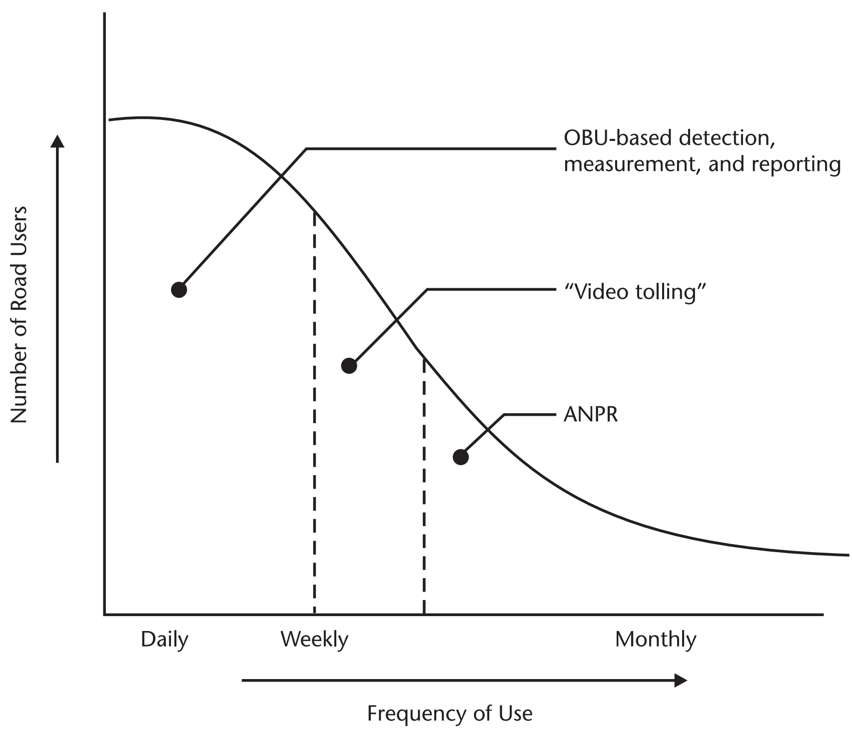

Figure 3.2 Technology choice and usage.

- OBU-measured usage or OBU-triggered charging events;
- Image-triggered charging events (video tolling);
- ANPR, enforcing a period licensing scheme (such as a day pass).

The importance of usage relates directly to the business case; higher usage is best satisfied with greater automation to capture the benefits of economies of scale and reduced transaction costs. This is analogous to capital-intensive mass production compared with handcrafted, low-volume production. The investment in OBUs (by the scheme operator and user) and related roadside infrastructure needs to be offset by the savings in transaction costs over the lifetime of the investment, as described below.

The boundary lines between the approaches shown in Figure 3.2 are not to scale, and will depend upon the transaction costs for each type of transaction, which in turn depend upon the investment in charging process capacity in each type and lifecycle costs for each subsystem. The relationship between data capture accuracy, the business case, and charging policy is also described in the following section.

3.5.1.1 Accuracy and Business Case

Frequent users of a road network generate more chargeable events, so it makes sense to use the most efficient, automated means of recording and reporting their road usage. This uses in-vehicle equipment where single-point capture accuracy is required, and video tolling or ANPR where multiple detection points are possible. The equipment costs are outweighed by the operational cost savings through more accurate and automatic recording of road usage. The cost to the road user (e.g., time, effort) is also reduced through this automation. The frequent road user and the ETC scheme operator both benefit from the use of OBUs (also called tags). The operational cost saving made by the operator can be shared with the road user in the form of a per-transaction discount, as offered to all EZ-Pass accountholders in the United States, for example. This can increase the adoption of OBUs, which further reduces the operational cost for each charging event. The data capture accuracy of an OBU (DSRC and CN/GNSS) is virtually 100%. With adequate security management this means that the data can be trusted, and used to levy a charge without any manual intervention. Overall encouraging regular users to adopt an OBU means that the highest possible volume of charging events can be automatically handled.

The cost/benefit ratio changes for infrequent road users. The cost of an OBU to an operator includes handling, personalization, packaging, distribution, replacement, and customer support. The adoption of tags by infrequent users would not make economic sense, unless the OBU could be made interoperable with other operators, or the toll charge is sufficiently high (e.g., the Storabælt Bridge in Denmark, where passenger vehicles pay €28 or $34 per crossing). ANPR offers the opportunity to identify the vehicle of an infrequent user by its license plate. ANPR can be used to enforce a charging scheme (e.g., London Congestion Charging), or can be configured for video tolling.

ANPR cameras typically have a low data capture accuracy, so video tolling relies on the capture of multiple images (e.g., front and rear license plates) at a single location to improve data capture accuracy for a single charging event. This requires manual validation to ensure that the charge is applied to the correct account (e.g., Melbourne City Link, 407 ETR, Cross Israel Highway).

Section 3.5.4 gives further information on the use of ANPR for charging.

3.5.1.2 Charging Policy

DSRC is typically used as the primary method of charging where a charge is to be applied at one of a discrete number of specific points, such as a toll plaza or a location on the open highway. Over 60 million DSRC OBUs are in use worldwide, mainly for ETC. The Austrian truck tolling scheme uses DSRC for segment-by-segment charging on motorways (see Figure 3.3).

Table 3.1 shows that enforceable, distance-based charging schemes from continuous measurements can be provided by a combination of GNSS (continuous measurement determination), CN (reporting), and DSRC (identification for enforcement). Accurate GPS-based position estimates can be compared with an on-board or off-board database of the road network to work out the most likely road segment on which the vehicle is traveling. Each road segment could have its own tariff (probably proportional to its length and time of day), which means that it is possible to determine the charge for the road segment. The OBU contains functions to filter out any noise in the measurements, the effect of reflections from nearby objects such as buildings, and distortions due to atmospheric disturbances.

Figure 3.3 DSRC charge point (LKW Austria). (Courtesy of Kapsch TrafficCom AG.)

The OBU may also be able to get external assistance data from the scheme operator that alerts the OBU to available satellites, and provides corrections for short-term distortions to improve the acquisition time of satellites. The acquisition time from an initial start is known as the time to first fix (TTFF). Section 3.5.3 discusses further variants to improve OBU positioning performance through augmentation. The alternative solution that uses only DSRC (i.e., discrete location determination and identification for enforcement) could be equally technically viable. The business case would reveal which is more economically appropriate, after considering the enforcement infrastructure for all methods of charging, the extent of the chargeable roads, quantity of vehicles, interoperability with other schemes, and the need for discrete DSRC infrastructure for charging compared with the operationally more complex GNSS OBU.

The distance traveled by a vehicle can also be based on direct measurement from the vehicle odometer, although this method alone does not identify the road type, so would not permit charges to be differentiated between road types. An in-vehicle OBU that incorporates a GPS module can be used to estimate the vehicle position, although positioning information by itself is not always accurate enough to determine distance traveled [2].

The Swiss heavy truck tolling scheme Leistungsabhängige Schwerverkehrs-abgabe (LSVA) has used a feasible hybrid solution since 2001, which relies on an odometer to measure the distance traveled by the vehicle, DSRC to turn on and off at international borders, and GPS to provide redundancy and to audit the odometer reading. Other variants are expected to emerge, depending on whether there are one or two tariff boundaries (e.g., motorways and other roads), or more than two boundaries (e.g., charges differentiated on all road types). The increased quantity of tariff boundaries generally increases the dependency on continuous positioning. The Austrian and U.S. schemes, including PrePass, Norpass, and Commercial Vehicle Information Systems and Networks (CVISN) [3, 4], depend on detection of the vehicle at discrete locations on strategic routes to enable the allocation of fees or gas taxes to the states in which trucks pass.

By comparison, the New Zealand truck tolling scheme [5, 6] is based exclusively on manually reading the distance traveled from a certified odometer fixed to the hub of trucks (all diesel engine vehicles), although this scheme is not able to identify the road type.

Overall, 6 million CN/GNSS OBUs are in use, with small-scale pilots for distance-related charging underway in Europe, the United States, Australia, Southeast Asia, and Japan, potentially for all vehicles. A sample OBU that incorporates CN, GNSS, and DSRC technologies is shown in Figure 3.4.

We can already see that simple requirements may need more than a single technology. These examples also show that technology choice is not a choice between charging technologies, but rather a selection of an appropriate bundle that meets local needs, and, if they exist, regional and national policies.

Sections 3.5.2 to 3.5.4 outline the three main technology groups. Section 3.5.5 deals with occasional users. The ability to roam between schemes that apply different charging policies depends on the regional interoperability strategy, as discussed in Section 3.6.

Figure 3.4 Hybrid GNSS/CN/DSRC Toll Collect OBU designed specifically for Toll Collect to be used in HGVS for in-dash mounting. (Courtesy of Efkon Mobility, Delphi Grundig, and Toll Collect.)

3.5.2 Dedicated Short-Range Communication

3.5.2.1 Background

DSRC is a localized, bidirectional, high-data-rate channel that is established between a fixed roadside system and a mobile device installed within a vehicle. The most widely used frequency bands for DSRC are 902 to 928 MHz (mainly North America); 5.8 GHz; or 5.9 GHz, depending on locally applicable standards; and infrared frequencies (mainly selected countries in Southeast Asia). See Table 3.2. Other frequencies have been used in the past, including 2.45 GHz (still used

Table 3.2 Variants of DSRC

Frequency Band (Primary and Secondary)	*Applicable Standards*	*Communication System*	*Dominant Regions of Use*	*Dominant Application Area*
5.850 to 5.925 GHz	IEEE P1609.1 to P1609.4 and ASTM- E2213-03 WAVE Platform	Active	United States	Road user charging and electronic toll collection
5.875 to 5.815 GHz	CEN DSRC Specifications	Modulated backscatter	Europe, South America, Australia, Southeast Asia	Safety, public services, road user charging, and electronic toll collection
850 nm (Wavelength)	CALM IR ISO CD 21214	Active	Malaysia, Taiwan (planned), and Germany	Road user charging and electronic toll collection
5.790 to 5.810 GHz and 5.83 to 5.85 GHz (primary); 5.770 to 5.790 GHz and 5.81 to 5.83 GHz (secondary)	ARIB STD-T75	Active	Japan	Electronic toll collection
902 to 928 MHz	Title 21	Modulated backscatter	United States, Canada, Mexico	Electronic toll collection

in Hong Kong and Singapore), and 850 MHz (SAW technology, initially used in Oslo, Norway). The standardization process saw the migration to 902 to 928 MHz (mostly the United States) and 5.8 GHz (Europe, South America, and Southeast Asia), using so-called modulated reflectance or backscatter techniques for communication. Since 1990, the Telepass-branded ETC system in Italy has been based on a single-vendor 5.9 GHz solution complying with a local standard [7]. The standardization of DSRC in Europe has been slow, although there are examples of national and cross-border schemes.

A modulated reflectance OBU is able to rapidly vary the reflective property of its antenna, which is known as a patch antenna, and is typically a single patch of copper less than 5 cm^2, to transfer incident RF energy generated by a roadside DSRC transceiver, back to the transceiver. The OBU does not generate any RF, but it merely modulates the reflected energy. When using RF or microwave frequencies, these systems work in a master-slave (S/M) mode. The roadside antenna transmits data to the OBU using a modulated carrier. When the OBU needs to transmit data, the roadside antenna transmits an unmodulated carrier signal, which is received by the OBU, modulated on the carrier, and then reflected back to the roadside antenna. The fact that the OBU reuses the signal from the roadside transmitter severely limits the range of the DSRC systems, since the attenuation of the reflected signal follows the R^4 power law (i.e., the received signal is attenuated by a power of four proportional to R, the range of the communications).

The use of modulated reflectance for communication allows the OBU to operate at very low power levels, requiring either a long-life battery (DSRC 5.8 GHz), or no battery at all (902 to 928 MHz), where regulations permit sufficient energy to be transferred to the OBU. The communication distance typically ranges from 10m to 20m. This is sufficient to enable localized, lane-specific communications at toll plazas and OBU localization for tracking and enforcement in open road charging schemes known as open road tolling (ORT), which is a combination of a toll plaza alongside open lanes, and multilane free-flow (MLFF), which is an open road without any plaza.

The most common applications of DSRC are electronic toll collection (ETC) at toll plazas and MLFF/ORT schemes, and as localized communication for enforcement as part of GNSS solutions (e.g., the German truck tolling scheme). Figure 3.5 shows a scheme that employs DSRC as the primary means of charging.

DSRC technologies have traditionally been considered as simply another payment option within the tolling application area. DSRC roadside systems (e.g., transceivers and lane controllers) have evolved to provide a simple (although proprietary) interface to existing toll lane equipment, along with magnetic and smart card readers, manual toll terminals (MTTs), and ACMs. The technology initially could only cope with very low vehicle speeds (less than 25 mph), and only limited amounts of application data could be exchanged between the OBU and DSRC roadside system (RSS). Following 20 years of development, speeds up to 100 mph/ 180 km/hr and integration with high-performance enforcement equipment is now considered routine, which is confirmed by the willingness of financiers to back MLFF schemes worldwide.

The main functions of a DSRC-based charging point, highlighted in Figure 3.5, are:

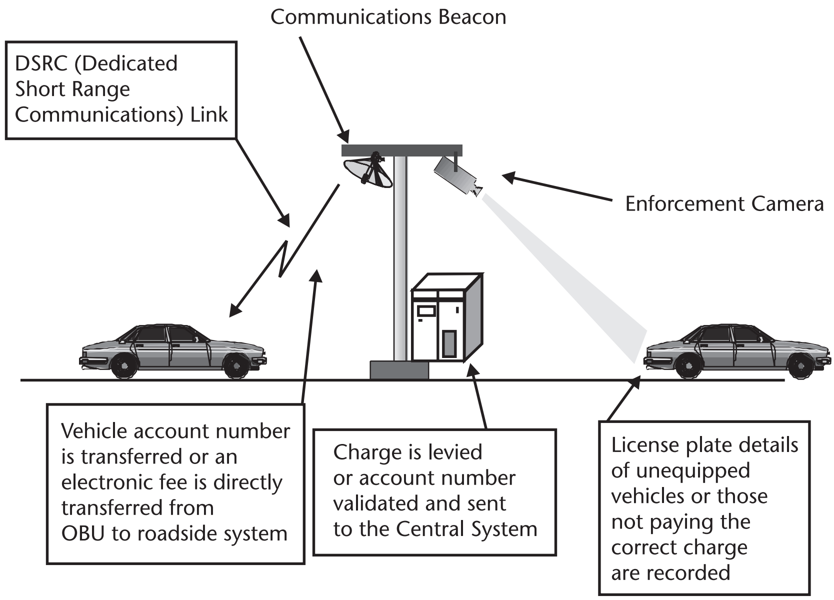

Figure 3.5 Schematic of DSRC scheme.

- Storage of account-specific and optionally vehicle-specific data within an OBU for declaration to a roadside system;
- Transfer of the OBU data to a roadside system over a directional DSRC interface;
- The ability to spatially localize the OBU in ORT/MLFF systems, or to limit communication to a single vehicle within the toll lane;
- Interpretation of the received information, packaging, and transmission to the central system;
- Detection and management of occasional (unequipped users);
- Capture of images, if any discrepancy is detected between the OBU's declarations, locally held account information, and direct measurements.

DSRC could be deployed at the boundary points between road types that are differentiated by charging rates, if the charging policy and functional requirements allow this. The number of boundary points (defined by the underlying charging policy) represents a significant cost factor for DSRC-based charging systems. For ETC, a significant cost factor is the number of toll lanes that offer ETC services. For all DSRC implementations, the number of tags issued is also a cost factor, although unit prices for at least 100,000 tags would be approximately €17 (approximately $21).

Triggered by the FCC's allocation of 75 MHz of spectrum to ITS applications, future U.S. development efforts [8] will include the 5.9-GHz band, with the active participation of the Institute of Electrical and Electronics Engineers (IEEE) and the American Society for Testing and Materials (ASTM) [9]. The most recent addition to DSRC is the IEEE P1609 family of standards [10–14] and ASTM E2213-03 [15], which comprise the 5.9 GHz Wireless Access for Vehicular Environments

(WAVE) platform. This platform uses active transceivers at both ends of the communication link to achieve operating ranges up to 1 km; although the focus is primarily on safety, it also enables a broad range of ITS applications, including ETC. The U.S.-led OmniAir consortium is developing certification specifications and related over-the-air transaction definitions to enable multivendor support for WAVE-compliant products. Prestandard WAVE products are being readied for application testing, ahead of the scheduled publication of IEEE 802.11p in June 2007 [16]. WAVE forms track 2 of the U.S. Department of Transportation (DOT)–led vehicle infrastructure integration (VII) initiative [17], which aims to incorporate communication technologies in all vehicles and on all major U.S. roadways. Consumer access to WAVE-related services will depend on collaboration with the automotive industry, and will be subject to the vehicle planning life cycles of these companies. Chapter 9 gives further information on WAVE and the VII.

3.5.2.2 Extended OBUs

Some OBUs have a modular design, facilitating add-on peripheral equipment (e.g., smart card readers, keyboards, displays, and connections to other in-vehicle equipment). Such OBUs were first developed in the early 1990s by the EU-funded ADEPT project [18, 19], led by the Transport Operations Research Group (TORG) in the United Kingdom, Sweden, Portugal, and Greece. The modularity in the design of these prototypes allows several different forms of payment (all of them cashless) with one device. Possession of this form of OBU offers users the possibility of holding a positive (or a limited negative) credit balance, either directly in the OBU's memory or on a separate smart card interfaced to the OBU. The smart card, being portable, can then be used for other payment purposes, and hold an audit record of incurred transactions.

The key limiting factor in on-board automatic debiting systems is the processing speed of the smart card. In Singapore, each charging point has two gantries: one to start communications with the vehicle and a second (further down the road) to complete the transaction and perform enforcement measures. Nevertheless, despite the speed limitations of mainstream products, smart card–based solutions are well proven in plaza-based ETC schemes in other countries, including Italy and Malaysia (see Figure 3.6). Turkey uses a smart card for in-lane use.

Schemes that use DSRC as the primary means of charging usually use ANPR as an enforcement system. The license plate is currently the only available unique identifier that can identify the vehicle if the charging equipment is not working properly, or is not installed. Chapter 4 discusses this further.

The Singapore ERP scheme, Melbourne City Link (Australia), Cross-Israel Highway (Israel), Costanera Norte (Chile), and Highway 407 (Canada) are the most familiar DSRC schemes, since they were the first in their respective regions.

The lowest cost OBUs are monolithic; that is, the only external interface is via an ultrahigh frequency (UHF), microwave, or infrared (IR) link. The payment transaction result traditionally was communicated to the driver via lights or variable message signs located in toll lanes. The evolution of multilane, open highway systems resulted in a simple interface being added to the OBU, typically a monophonic beep and light emitting diode (LED) indicators. Enhanced versions have a

Figure 3.6 OBU with integrated smart card reader. (Courtesy of Q-Free.)

direct external interface to the vehicle (as demonstrated by the ERTICO-led DELTA project [20]), a utility serial interface, multilane display, and an integrated smart card reader.

The current markets served by DSRC have the following typical characteristics and requirements:

- *Focused application:* The systems should support tolling in single lane environments, and tolling and road user charging in ORT/MLFF environments.
- *Inexpensive end-user equipment:* Low-cost, mass-produced OBUs should have an operational lifetime of at least 5 years (ideally 7 years).
- *User-installed:* OBUs are designed to be distributed through retail outlets, automated vending machines, or by post. This ensures high market penetration with limited (or no) installation support from the highway operator, although there is always a risk that a small percentage of the units will be incorrectly fitted.
- *Minimal interface capability:* Minimal interaction with the user is required.
- *High speed:* Performance should be predictable and reliable in constrained low-speed toll lanes and in high-speed (typically more than 100 mph/180 km/hr) lanes. Transaction error rates are claimed to be less than 1 in 10 million in MLFF environments.
- *Harsh environment:* They should be capable of operation between extremes of ambient temperatures, from parked vehicles sitting in direct sunlight to subzero temperatures.
- *Autonomous:* The OBU is simply fixed to the windshield using a proprietary holder, with no interface to the vehicle. Tamper detection is available.
- *Low lifetime cost:* Battery life should range from 3 to 10 years for a simple interface. The roadside system can notify the user at a DSRC charge point by a simple audio/visual indication to return the OBU to the issuer at a predetermined time interval for a replacement unit.

- *High volume:* An estimated 60 million units have been deployed worldwide, with typical project batch sizes between 50,000 and 100,000. Start-up volume batch sizes are sometimes greater, based on forecasts of initial adoption rates.
- *Limited support for other ITS applications:* The limited communication range of modulated reflectance devices (from 10m to 20m, depending on applicable standard) means limited support for other ITS applications. The WAVE platform promises a range up to 1 km.

Competition for large-scale projects between 1996 and 1999 in the United States led manufacturers to compete on OBU unit price rather than on roadside system price. This precedent impacted European vendors, leading to an early establishment of a unit cost (to a highway operator) of between €17 and €30 (approximately \$20 to \$36) for OBUs, which is estimated to fall to less than €15 (approximately \$18) within 5 years.

Specialized OBUs are also available to meet local requirements, including:

- Taxi-Tag available from Melbourne City Link (Australia), which increments the taxi meter with total charges for the trip;
- Explosion-Proof OBU required by Dartford Thurrock Crossing (United Kingdom) for petrochemical fleet operators;
- Motorcycle OBU offered by the Singapore Land Transport Authority (LTA), comprising a weatherproof enclosure to protect the smart card and balance display;
- OBUs with mounting brackets for passenger cars and heavy goods vehicles with various types of windshields;
- External antenna OBUs, offered by Autobahnen und Schnellstrassen-Finanzierungs-Aktien Gesellschaft (ASFINAG) (Austria) to trucks that have metallized windshields;
- An OBU with an external connector to allow a manual lane operator to read the tag without a DSRC reader; for example, a simple serial interface and display used by some Télépeage Inter-Société (TIS) operators in France to access on-board data.

These variants do not modify the DSRC interface and therefore do not impact the communications interoperability with roadside equipment. However, the different mechanical configurations and display capabilities limit the direct exchange of one manufacturer's tag for another, although this is rarely an issue.

The impact of standards, the development of interoperability specifications, and the separation of procurement of roadside systems from OBUs have broken the interdependence between pricing strategies for OBUs and roadside systems. The legacy of this is a broad array of OBUs, differentiated by cost, brand name, user interface, and availability of an integrated reader smart card. The most important factors in a global market are unit cost, standards compliance, and ability to meet interoperability specifications, although isolated schemes may continue to benefit from proprietary solutions.

3.5.2.3 Failure Rates

The main cause of failure of a DSRC transaction at a single point of detection is incomplete or no communication with the roadside system.

Under a controlled environment, using systematic testing with trained drivers, the probability of incomplete or no communications is typically 0.005%. Under live conditions at several MLFF DSRC projects (i.e., optimal geometry), the long-term average is between 0.3% and 0.5% at a single point of detection. This error rate can be reduced in proportion to the number of detection points along a defined route by logically rebuilding the journey between locations where the OBU was detected.

The most common causes of incomplete or no communication failures are as follows:

- *Incorrectly mounted OBUs:* This can be mitigated by high levels of user compliance achieved by clear installation instructions, and by associating OBUs with specific vehicles.
- *Unmounted OBUs:* OBUs may be on a dashboard, on the seat, or held in the hand. This can be mitigated by making it more difficult to swap tags between vehicles (contractual restrictions), and suppression of the user's belief that the OBUs contain value.
- *Dead OBU (faulty):* This can be mitigated by encouraging road users to contact the operator if the OBU does not provide any audible notification at a charge point.
- *Dead OBU (battery):* This can be mitigated by battery management within the OBU. Examples include shutting the battery down automatically when the terminal voltage reaches a predetermined level, notification to the driver to return the OBU to the operator, battery voltage monitoring and reporting, low-battery fault monitoring, and activity timers for reactive OBU management methods. These policies permit the road operator to plan in advance when to replace an OBU to reduce the probability of in-service failure.

3.5.2.4 Integration with Enforcement

Figure 3.5 highlighted typical features of a DSRC charge point with enforcement capability. The geometric arrangement of communications, vehicle detection, classification, and enforcement permits vehicles to be detected, tracked, and spatially paired with OBUs at the point of charging. Depending on the charge point configuration, vehicles may be tightly constrained within a toll lane, which simplifies the enforcement function. The DSRC subsystem merely has to confirm that the OBU declares sufficient information to be consistent with an in-lane vehicle classification subsystem, and associate the OBU with a valid account. Vehicle detection and (optionally) classification subsystems with unconstrained toll lanes are required to provide spatial information, which enables a vehicle to be matched with an OBU localized with the DSRC subsystem. The precise methods of the matching process are dependent on the vendor and project. Figure 3.7 shows an example from Stockholm, and Figure 3.8 shows an example from London, both of which employ matching techniques.

Figure 3.7 Communication and enforcement (Stockholm Congestion Charging Pilot, Sweden). [Courtesy of ITS (UK).]

The Stockholm pilot system configuration was based on a cordon of 18 entry points corresponding to 39 separate charge points. The figure shows the largest site, covering nine travel lanes. The site configuration includes lane-centric, laser-based vehicle detectors (center gantry) that trigger a corresponding ANPR camera (nearest gantry) as the vehicle approaches. This enables the camera to capture an image of the front license plate, while accurately truncating the image to remove information on the driver. A rear ANPR camera captures the rear license plate when the rear of the vehicle is detected by the same vehicle detector. This configuration of gantries enables highly accurate vehicle detection and high availability ANPR, and is a result of the policy requirements for the tax (not a charge) collection scheme.

The London charge point is located on a single pole/outrigger for aesthetic purposes, since many of the charge points are located in or close to residential and commercial sites. The geometric configuration of the charge point shown permits spatial matching of vehicles with their corresponding OBUs. Note that Figure 3.8 is part of a DSRC technology trial in London, not part of the operational London Congestion Charging scheme described in Chapter 8.

3.5.3 Cellular Networks/Global Navigation Satellite System

3.5.3.1 Background

The generic term for the satellite systems used for positioning or navigation is GNSS. GNSS technology within an OBU estimates position by combining measurements of

Figure 3.8 Communication and enforcement (Trial Urban Charge Point, London).

signals from a constellation of orbiting satellites, typically GPS or the Global Orbiting Navigation Satellite System (GLONASS).[1] CN refers to the bidirectional communication between an OBU and a fixed network of terrestrial transmitters, usually commercial cellular services, such as CDMA, GSM, or Universal Mobile Telephone Standard (UMTS) [third generation (3G) in Europe] mobile telephone networks [21]. GNSS-based charging also requires the creation and maintenance of a digital map of the chargeable road segments, since the position of a vehicle for charging purposes needs to be related to these segments.

In theory, positioning and communications can be continuously provided services, although in practice both are subject to the uncertainty of radio coverage (i.e., a sufficient number of satellites are not always visible, and cellular networks do not have 100% coverage). The positioning function needs to be specified (possibly with assistance and augmentation), such that it is able to accurately identify the road segment on which the vehicle is traveling, or at least flag when an accurate position cannot be determined. The reporting strategy needs to indicate that cellular network coverage is not always available (e.g., lack of coverage, loss during cell handover, or lack of available capacity). Alternative methods of reporting may need to be considered, such as batching data to be subsequently exchanged with the OBU, or requiring the user to transfer the data by memory card.

1. GLONASS is operated by the Coordination Scientific Information Center (KNITs) of the Ministry of Defense of the Russian Federation.

CN/GNSS reflects a combination of technologies, in which OBU position estimation is reported to a central collection hub site, otherwise known as a technical back office. A DSRC transceiver is usually also integrated, allowing the OBU to communicate with fixed and mobile enforcement points.

A generic positioning system uses radio transmissions to estimate position. The first areawide navigation systems used ground-based transmitters to provide reference signals for measurement. Although terrestrial positioning systems are still widely used, satellite-based transmitters are used to cover the majority of the Earth's surface, and provide positioning information with higher accuracy than from terrestrial systems. The satellites transmit timing information, satellite location information, and information that describes the health of individual satellites. The *Space Segment* is the technical term for this constellation of satellites. The most widely used satellite constellations are GPS and GLONASS, sponsored by U.S. and Russian government agencies, respectively. A third constellation, known as Galileo, funded by a consortium of member states of the European Union and others, will commence service in 2008, and will interoperate with GPS. Figure 3.9 shows the main elements of a scheme that uses CN/GNSS as the primary means of charging.

Every GNSS system employs a constellation of orbiting satellites working in conjunction with a network of ground stations. Every OBU requires a special radio receiver that is able to receive and decode the transmissions from visible satellites. This receiver uses triangulation to locate the OBU by combining information from a number of satellites, each of which transmits specially coded signals at precise intervals. The difference in time for signals to be received from the visible satellites is used to calculate the relative distance that the receiver is from each satellite. Using this information, and the fact that the receiver accurately knows the location

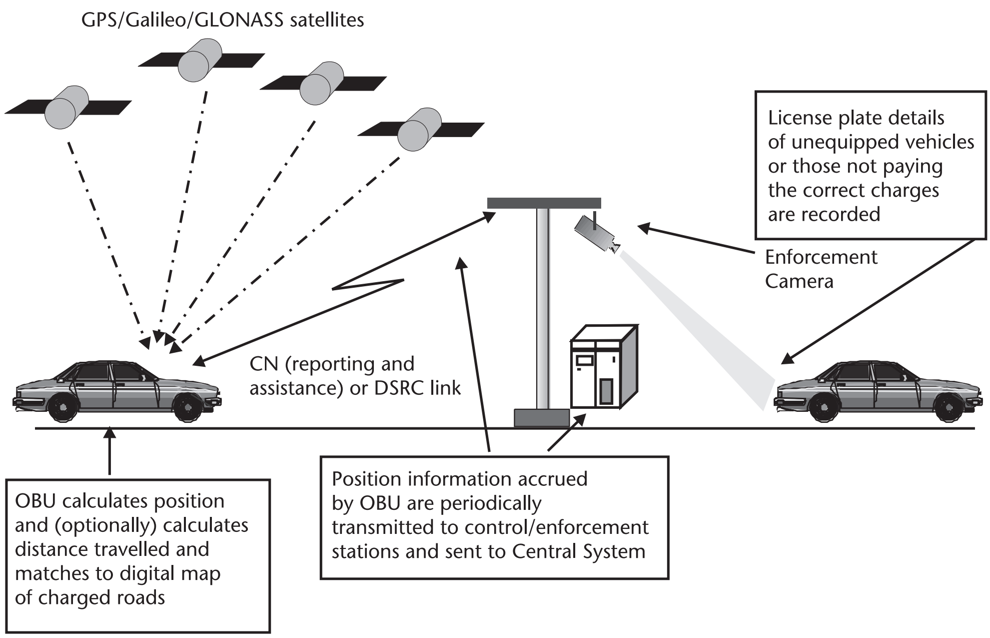

Figure 3.9 Schematic of a CN/GNSS scheme.

of each satellite and any time and point on its visible orbit, the location of the receiver in the vehicle can be calculated. The receiver converts this signal information into the position and velocity of the receiving OBU and provides an estimate of time. The OBU calculates its own position by coordinating the signal data from four or more satellites captured at about the same time. A minimum of three satellites is required to calculate location on the Earth's surface, while a fourth satellite signal enables the height above the Earth's surface also to be calculated. In practice, the receiver utilizes the signals from as many satellites as are in view practically a maximum of 12 to 13, to help overcome errors and ensure accuracy. The users (i.e., the OBUs) and their receivers are collectively known as the *User Segment*. The satellites are controlled and monitored from several ground stations, which are collectively known as the *Control Segment*. These stations monitor the satellites for health and timing accuracy, and are able to upload maintenance commands, orbital parameters, and timing corrections as needed.

It is important to note that the user does not have to transmit anything to any satellite, and that the satellites do not have the capability to track OBUs. The space segment does not need to know of the existence of the OBU, since the OBU is merely a receiver of a broadcast signal. Thus, there is no limit to the number of receivers, including OBUs, that can use the system at any one time. A typical GNSS/CN OBU for windshield mounting is shown in Figure 3.10.

The GPS and GLONASS systems each provide two sets of positioning signals with different degrees of accuracy. The higher accuracy signal was originally reserved for each country's military use, and the lower accuracy signal was available to civilian users without charge. On May 1, 2000, this restriction was removed from GPS. By comparison, the business model for the future Galileo operation is likely to be based on different service levels linked to escalating fees. The services offering the highest accuracy and availability will be charged, although general positioning capability will be offered without charge at the point of reception. Galileo will also provide an integrity indicator, so that the OBU will know whether

Figure 3.10 GNSS/CN OBU for windshield mounting. (*Source:* Siemens.)

the received signals can be trusted. This ensures that position estimates and the charges related to the vehicle's position will be credible. GPS integrity monitors are already available, although most have limited benefit.

3.5.3.2 Performance

The quality of the positioning information from a satellite radio receiver inevitably varies over time and by position of the measuring device, so we should assume that the location could only ever be regarded as an estimate. The quality of the output from GNSS depends on accuracy, yield, and latency.

- *Accuracy* is the linear offset between the actual position and position estimate, when available.
- *Yield* (0% to 100%) is the probability of providing a location estimate within a defined time period.
- *Latency* is the time from a position request to the availability of a location estimate.

Accuracy, yield, and latency are interdependent and depend on several factors:

- Time of day, since the space segment constellation geometry varies throughout the day;
- Atmospheric disturbance;
- Impact of local environment (e.g., multipath or occlusion within tunnels or urban canyons);
- Nonoptimal orientation of GPS antenna and attenuation by vehicle;
- Local multipath interference;
- Integration time of receiver;
- Instability and offset of receiver clock.

Many reports [22] into the performance of autonomous GPS in widely varying environments are based on receivers that track satellite integration times in excess of 20 minutes. However, time-critical applications, such as accurately detecting when the vehicle has crossed a tariff boundary, may require the maximum latency to be no greater than 10 seconds, and the position of the OBU relative to a charged area to be known to within 99% certainty (or better). The implementation of a charging policy may sometimes require a road segment to be identified, possibly based on several independent measurements by the same OBU over a short period, and then matched by position and direction of travel to the location and orientation of a road link that is recorded on the on-board or off-board map database. The corresponding charge can be calculated from the identity of the road segment, length, and the tariff at the time of travel.

The ERTICO-led road charging interoperability (RCI) initiative places requirements on positioning accuracy of GNSS subsystems: 95% of location estimates shall lie within 20m of the true position [23]. This technical accuracy underpins the charging accuracy based on road segment identification. Although the technical accuracy is important to ensure operational integrity, the scheme operator and road user are more interested in the billing accuracy, which depends on all road segments being correctly reported. The accuracy requirement for missed or incorrectly reported road segments creates a requirement on two parts of the operation:

- The positioning accuracy (relative to the correct chargeable road segment);
- The accuracy of the charges actually levied on the road user by the central system (see Section 6.2.3) as shown in Figure 3.11.

If the positioning accuracy is not sufficient to correctly identify the road segment (e.g., two parallel roads having different tariffs), then the final bill will be wrong. This may be mitigated by several methods, such as providing additional local augmentation at difficult locations on the road network (e.g., the German truck tolling scheme uses IR beacons to broadcast the identity of some road segments); auditing a vehicle journey to identify apparently missed or inconsistent road segments; or using the integrity information to decide whether or not to use a position estimate.

Both the Swiss LSVA and German truck tolling schemes employ GPS to provide continuous vehicle position information. As described above, the Swiss system uses the vehicle's odometer as the primary means of determining road usage. DSRC is used to enable and disable distance measurement and for enforcement. Figure 4.7 shows an example of a Swiss enforcement point. GPS provides a redundant backup to the odometer and DSRC functions, and confirms that the odometer is switched on and recording. The German scheme uses a mix of GPS to identify the road segment on which the vehicle is driving based on an on-board map database, and, where GPS is not available or where chargeable and nonchargeable roads are in close proximity, roadside infrared DSRC beacons provide localized fill-in information.

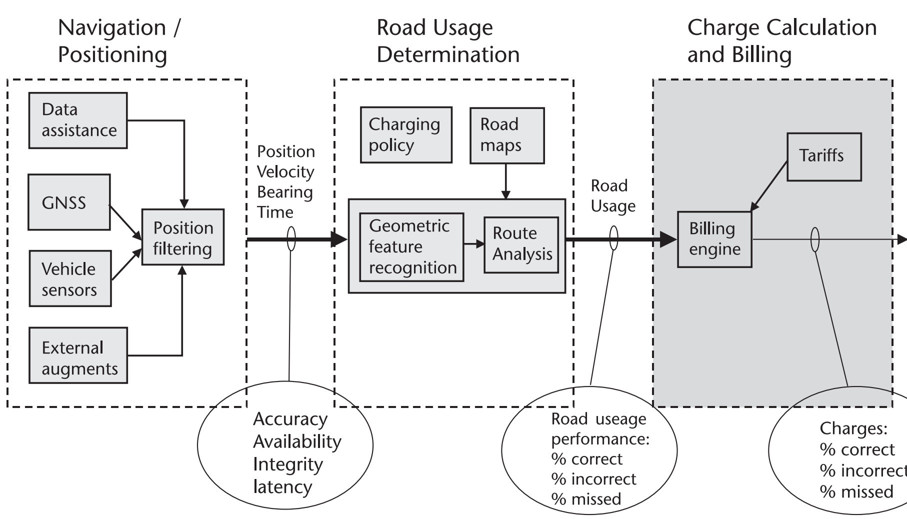

Figure 3.11 Positioning, usage determination, and billing. (*Source:* Mapflow, 2006.)

3.5.3.3 An Intelligent Client or a Thin Client?

There are primarily two types of GNSS OBUs, which differ in the division of tasks between the in-vehicle equipment and the roadside systems. The minimum requirement on the OBU is to capture satellite data and estimate a position. The minimum requirement on the central system to which the OBU reports is to allocate the total aggregate charge to the appropriate account. The ERTICO-led RCI group allocates the following tasks to either the OBU or the central system:

- Getting processed sensor data;
- Comparing data to determine location;
- Calculating charging data;
- Aggregating charge data up to thresholds.

Although the definitions of thin and intelligent have not been standardized, it is generally accepted that an OBU that estimates position and matches this to the terrestrial data of road segments is known as an intelligent client. The OBU is required to maintain a database of the road network on which the vehicle is likely to travel. The alternative approach limits the OBU to estimating its position, temporarily storing this information on-board, and subsequently reporting this data with corresponding time stamps to the central system to be matched with a map database. This is known as a thin client.

Table 3.3 compares intelligent and thin clients.

Technology vendors each make competing claims on the benefits of each system. Thin clients delegate much of their responsibility to an intelligent central system, and are the current direction of development for the delivery of location-based services for mobile phone users [24]. Thin client OBUs do not require a locally maintained map database, but still communications traffic from OBUs to the central system. 2.5G and 3G cellular networks are able to support this capacity. The same evolution in communication services benefits intelligent clients, which are chosen for both the Swiss and German truck tolling schemes.

Table 3.3 GNSS: A Comparison of Intelligent Versus Thin Clients

*Intelligent Client**	*Thin Client*
Position estimation, map matching, and reporting	Position estimation and reporting
On-board map database and tariff table, with possibility of outdated versions	No on-board map database or tariff table
Summary reports only (road segments)	Detailed reports (time-sequenced position estimates)
Potentially lower communications for reporting, offset by increased updates of map database and tariff tables	Potentially greater communications overhead and related costs, offset by no need to retain map database and tariff table updates
Near-real time display of accumulated charges	Charge only determined when report has been transmitted to central system

*Known also as a thick client to reflect its complexity compared with a thin client.

3.5.3.4 Improvement Through Augmentation

Additional factors improve the accuracy of the location estimate: data assistance from overlay services and cellular network, application augments, and complementary technologies. Each is discussed next.

Data Augmentation

Additional overlay satellite services are available to correct GPS signal errors caused by ionospheric disturbances, timing errors, and satellite orbit errors. The confidence that an OBU can attach to position estimates depends in part on the health of each satellite. Overlay services can also provide integrity information regarding this health. North American users have access to the Wide Area Augmentation System (WAAS) [25], European users have the European Geostationary Navigation Overlay Service (EGNOS) [26], and GPS receivers in East Asia have the Japanese Multifunctional Satellite Augmentation System (MSAS). Other comparable overlay services are available in India and China.

Terrestrial radio networks (i.e., a commercial GSM or CDMA network) can provide assistance to the terminal, either on-demand or broadcast periodically. This is referred to as Assisted GPS (A-GPS). The assistance data provides the OBU with knowledge of available satellites, along with corrections for time and atmospheric conditions. Assistance can therefore reduce the receiver search time, increase the number of valid observations (to increase the probability that a location can be computed with better geometry), and increase the accuracy of the observations available within the GNSS OBU.

A-GPS is a new technology that capitalizes on extensive development into the GPS network, and has driven the growth in expertise serving the emerging consumer and commercial markets for autonomous GPS terminals. These historically stable markets are vertically oriented among a very limited number of fabless[2] licensors of chipset designs/Intellectual Property, chipset vendors, and system integrators. This leads to a concentrated supplier base for GPS-based products.

A-GPS is a variant of autonomous GPS, which aims to compensate for measurement offsets, reduces the TTFF waiting time for a location estimate, and will provide a small improvement in received sensitivity to increase the number of visible satellites. Increasing the quantity of satellites that are visible to the in-vehicle receiver will improve the location geometry and reduce the error in locating a terminal that is partially or fully obscured from the sky (e.g., inside a tunnel or covered parking garage). A moving vehicle may travel down an urban canyon, where the view of the sky is restricted by tall buildings or nearby high vehicles. Poor location geometry increases the receiver's horizontal dilution of precision (HDOP). This means a higher uncertainty for each position estimate.

Visibility of more spatially distributed satellites will improve the geometry of the positioning calculation, particularly in urban canyons. The addition of more satellites (e.g., commencement of Galileo services) will have the same effect, and is expected to increase the time for which dual mode receivers are able to see more satellites (of either type).

2. Fabless literally means without fabrication, generally applied to a chipset designer that licenses designs to manufacturers.

Application Augmentation (Map-Matching and Interpolation)

The following application-level enhancements are available:

- Spatial analysis and map-matching, to snap the position or trajectory to the nearest viable road or route, often used for navigation applications (Figure 3.11);
- Knowledge of direction of travel (bearing) and logical connection between routes;
- Prediction (estimate based on fragmented data) and interpolation (estimation between data points) during temporary reporting.

The importance of estimate of position to RUC depends on the functional requirements of the system. If the charging policy is based on distance traveled according to the total length of road segments, then the accuracy of identifying the correct road segment is critical. The length, duration of time on the segment, and its directional uniqueness may be sufficient to enable the OBU to identify the road segment, even in areas of high uncertainty. Detecting the position of a tariff boundary (e.g., entering a charged area) would require higher accuracy, since the receiver is attempting to identify a transitional event at a precise location (i.e., a point), rather than attempting to identify a road segment (i.e., a line). The receiver may also be required to identify the zone (i.e., an area) in which the vehicle is located, rather than the point of transition. A scheme operator may require 99.99% confidence that a vehicle/OBU is within a chargeable area. To achieve a more relaxed confidence level of 99.9% would require an error margin of at least a 60m buffer zone in one case [27]. A thinner buffer zone would increase the probability that the OBU is not within the zone, but may be at either side of the buffer zone. To be confident that the OBU is within the prescribed area, the OBU must be positioned at least within the thickness of the buffer zone within the chargeable area—hence the term *buffer zone*.

The use of GPS in the urban environment for tariff boundary detection has currently focused on autonomous GPS [28, 29], although data and application augmentation (including with map-matching) is likely to improve performance where satellite visibility is limited.

The probability that the location estimate is close to the true position is shown in Figure 3.12, which also shows that the position error could be large for a small proportion of estimates. Figure 3.12 shows length (abscissa) as a proportion of the RMS error to illustrate the general distribution independently of the distance error. Improving the accuracy of a location estimate is not simply aimed at reducing the average or 1-sigma [63% circular error probable (CEP)] uncertainty; rather, it is aimed at reducing the area under the "long tail" in Figure 3.12, maximizing the geographic area over which the improved accuracy is available, and reducing the time taken to deliver an estimate with improved accuracy.

Accurate location estimates result in improved charge calculation accuracy and an enhancement to scheme credibility, reinforcing the need for augmentation.

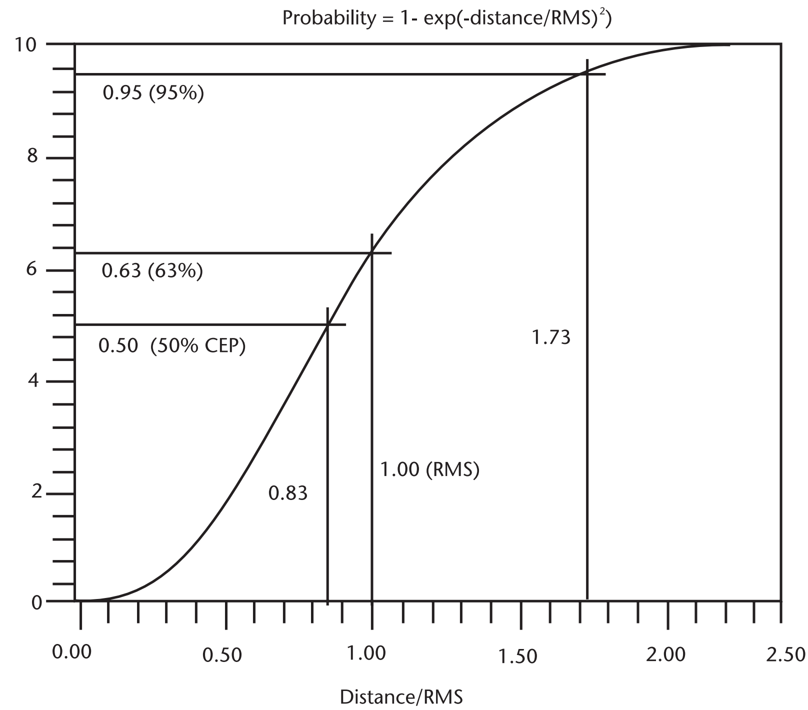

Figure 3.12 Distribution around true position.

Complementary Technology Augmentation

Map-matching and long-dwell integration are two of the methods that are known to reduce the position error from GPS. Other methods that will also improve accuracy of GPS and Galileo include:

- Dead reckoning, a proven method appropriate for vehicles traveling on a fixed route, which allows linear measurement to accurately restrain position measurements along the route;
- Direction sensors [9];
- Inertial aided technology (IAT), which allow continuous positioning despite variable satellite visibility in dense urban environments [30] (e.g., solid state angular rate sensors, and force-feedback accelerometers to provide additional information including velocity and acceleration);
- Hybridization with other terrestrial location methods, such as ground-truthed (i.e., calibrated performance), enhanced (or advanced) forward link trilateration (E/AFLT), CDMA, E-OTD, and Cell ID.

Wireless LAN receivers, such as 802.11g, can provide microcell location capability when cell ID is not available, but its usefulness is limited by the hotspot coverage in any area (currently limited mainly to areas of high population density, rather than road network density).

3.5.3.5 Long-Term Enhancements

The following improvements to the U.S.-operated GPS infrastructure are planned over the next few years, each of which will increase accuracy and geographic availability, and reduce latency:

- Signal improvements;
- New civilian frequency bands;
- Improved network stability;
- Improved network redundancy;
- Signal transmission efficiency;
- Antijamming and antispoofing (expected to be for military use only);
- Interoperability with Galileo.

Natural design improvements in GPS chipsets; increased bearer capacity to reduce opportunity cost of delivering assistance; massively parallel receiver arrays to increase the spectral window of receivers; potential deployment of "pseudolites" (i.e., fixed transmitters that provide ranging information to mobile devices, such as OBUs); and use of cellular picocells in the urban environment are all expected. If GPS receivers are built into vehicles as original equipment, then the optimum positioning of the antenna will most likely improve performance.

Galileo is expected to deliver higher accuracy and quality of service than the current version of GPS, although this may not be achievable by the free Galileo services. EGNOS commenced operation in 2006 to supplement GPS by reporting on the reliability and accuracy of GPS signals. This offers the potential that position measurements within OBUs or data correction processes within the central billing systems, will have a sufficient integrity to be usable for billing purposes. Whatever the intrinsic accuracy from a particular GNSS might be, increasing the number of satellites will be better. The situation will improve considerably with Galileo if the position measurement equipment can receive both GPS and Galileo (and GLONASS) signals. More satellites mean a high probability that enough will be visible and geographically spread in orbit to derive a location estimate with a lower error, rather than if fewer, poorly spread satellites were visible for only part of the time.

Terrestrial positioning based on cellular networks can reduce the ambiguity, or augment other methods of positioning to the resolution of a cell or cell sector, but cannot be used by itself to accurately measure distance. Terrestrial positioning methods are discussed next.

3.5.3.6 Support from Terrestrial Positioning Systems

The main methods of positioning based on 2G and 3G terrestrial cellular networks are:

- Cell ID and Timing Advance (Cell ID + TA);
- Enhanced Cell Global Identity (E-CGI);
- Enhanced Observed Time Difference (E-OTD).

The Cell ID is the identification of a cell, as designated by the network operator. This information normally defines the serving cell (connection point) of a cellular transceiver within a network. The network operator knows the coordinates of each cell site, or base transmitter station (BTS), that is used as a proxy for the estimated position of the cellular transceiver. However, cell sizes vary considerably across networks and between cellular technologies. Larger cells, referred to as macrocells, are typically tens of kilometers in radius in rural areas, while only a few kilometers in radius in suburban areas. Densely populated urban areas often deploy microcells that range from 100m to 500m to increase local capacity. Picocells can be deployed in buildings, offering a cell radius of tens of meters.

Some cells are split into three sectors, with each sector antenna pointing in a different direction, enabling a transceiver location to be estimated more accurately than from an omnidirectional cell. A parameter known as timing advance (TA) is used in normal GSM operation, and is a crude measure of the relative range of the connected mobile from the cell site to the cell boundary. This is accurate to a resolution of approximately 550m. The overall accuracy of Cell ID depends primarily on the accuracy of the BTS coordinate database, and can be improved by sectoring, use of TA, and signal strength information from more than one BTS. As a minimum, Cell ID and TA are parameters that are available for all mobiles in all networks.

The accuracy of a terrestrial positioning system depends upon:

- Density of BTSs;
- Size of cells;
- Layout of a network;
- Multipath of signals from BTSs;
- Shadowing and blocking;
- Geometry of BTSs.

An indication of the level of accuracy of a location estimate of the OBU can provide an indication of the estimated quality of the position estimate. For GSM-based positioning, [31] defines several shapes that can define the uncertainty region centered on the location estimate (see Figure 3.13).

The boundary of the shape for GSM represents the degree of uncertainty (i.e., the likelihood of the GSM receiver being within this area), at 67% or 95% confidence levels. GSM 03.32 [31] describes several shapes, including circles, sectors of a circle, segments of an arc, and ellipses. The location estimate could be weighted according to the degree of uncertainty to be used to determine the trajectory or position of a vehicle/OBU.

The accuracy of a GSM E-OTD system is between 75m and 100m 67% of the time. TOA and AOA hybrids are similar on 2G networks. Proposals were made for tolling systems based on charging for entering a radio cell, with the first trials being held on the A555 Köln–Bonn autobahn in 1996. Until recently, this option could be discounted, since this method could not offer sufficient accuracy in locating its position at any given time. This may change with the potential locating function that will be inherent in the 3G licenses for mobile terminals.

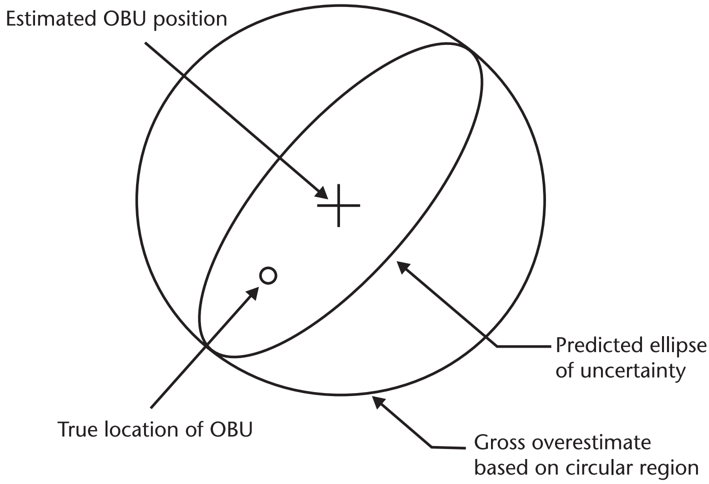

Figure 3.13 Area of uncertainty, centered on the location estimate.

3G mobile network operators claim a location service for business phone users with a 10-m accuracy, which is ample for road use charging purposes, although evidence for enforcement and prosecution may require a greater accuracy. Nevertheless, current versions of 3G phones in tests in Newcastle [32], and the extensive trials undertaken in London in 2004 to evaluate potential future technologies for an extension to the London Congestion Charging scheme, suggest that location accuracy is approximately several hundred meters [33], which is not nearly enough to operate a credible scheme and deliver credible evidence for the prosecution of nonpayers. Nevertheless, since mobile phones already have secure access and a central payment facility (as well as established interoperability), the technology needs only to provide more accurate location, and a robust and validated security and enforcement scheme, to be considered as a future contender [34].

Simple terrestrial positioning, such as Cell ID, can be used by a GNSS/CN–based OBU to request assistance data from an Assistance Server or Serving Mobile Location Center (SMLC) within the central system. The value of assistance data to an A-GPS–capable receiver in the OBU also depends on the location of the OBU, and the availability of visible satellites depends on the position of the GPS receiver. If an A-GPS receiver is capable of reporting (or allowing the cellular network to report) a coarse position based on the serving Cell ID, then the assistance data can be made more relevant, resulting in an improved TTFF and improved HDOP. This means a more rapid calculation of location from switch-on, and marginally improved accuracy.

3.5.3.7 Integration with Enforcement

The integration of a GNSS/CN–based charging solution with enforcement is similar to that for a DSRC-based solution, described in Section 3.5.2.3. The primary difference is that the calculation and reporting of road usage is physically separate from the enforcement solution; any fixed and mobile enforcement points can be independent of charging.

Regardless of technology differences, the objectives of enforcement remain the same: detecting noncompliance, providing a deterrent to nonpayment, and revenue recovery. Detecting noncompliance and capturing evidence of a vehicle's position at a specific location and time requires the vehicle to be identified, and (if fitted) the OBU to be interrogated locally to check correct functioning of the OBU, that road usage is being recorded, and that a valid means of payment is available.

3.5.4 Automatic Number Plate Recognition

ANPR systems process the video images taken by a camera in a lane, at the roadside, or on a gantry, to locate the license plate in the image and convert this into the appropriate alphanumeric characters, without any human intervention (see Figure 3.14). The significant advantage of such an approach is that it removes the need for any in-vehicle equipment to be installed, although the business case for this or any other solution needs to be justified (see Section 3.5.1.1). It also provides a solution for the occasional users (i.e., those who do not have the necessary in-vehicle equipment to automatically pay the charges), as described in Section 3.5.5. ANPR is a variation on the automatic account identification system, which relies on the vehicle's license plate as its unique identifier.

The increasing use of video cameras for road traffic monitoring has been an incentive to improve camera technology and optical processing, which is necessary to provide better contrast clearer images, even when the license plate is in a dark shadow, in the glare of low angles of sunlight, or surrounded by bright headlights

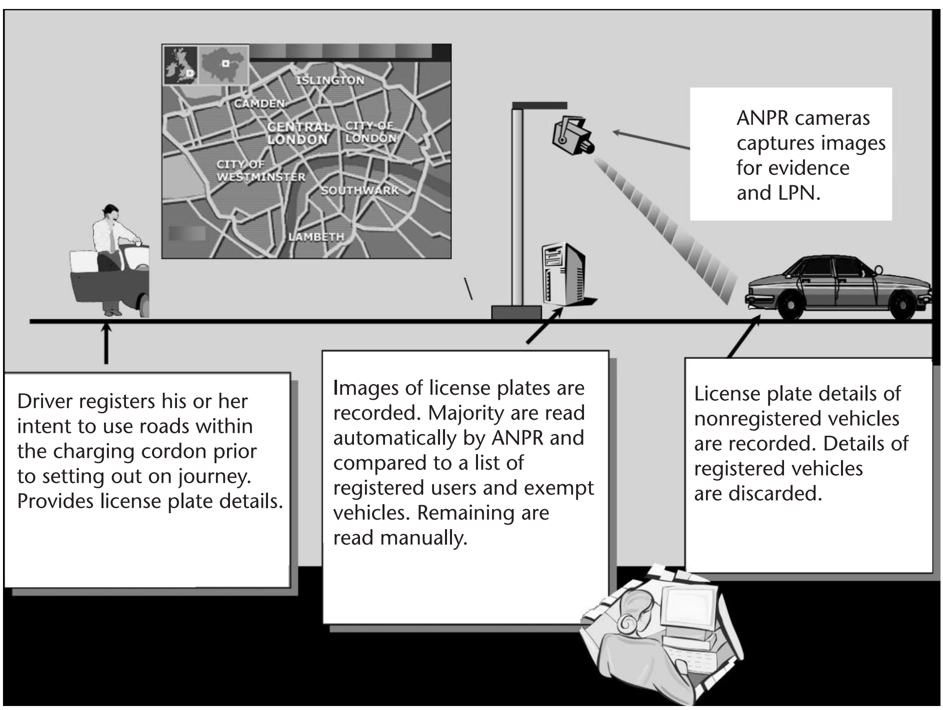

Figure 3.14 Schematic of an ANPR system.

in direct alignment with the camera. To improve accuracy and performance, the technical challenges facing ANPR technology vendors also include:

- License plates of many and different shapes and sizes due to lack of regional standardization;
- Nonreflective license plates;
- Dirt and poor weather, including rain and snow;
- Nonstandardized fonts;
- Similarities between some letters and numbers (e.g., O and D, B and 8);
- Insufficient control of ambient light at camera positions.

Some vendors capture multiple images to improve overall accuracy. If ANPR determines the same plate information for all images, then the confidence level of the data is improved and the need for manual interpretation reduced. Any discrepancies are either placed in a queue for visual inspection or treated as a "lost revenue" transaction. A Government Office for London Report [35] reviewed the road use charging options for London [the Road Charging Options for London (ROCOL) report] in 1998 and 1999. It studied the feasibility of road use pricing and workplace parking charges, as well as the likely impacts on business, traffic levels, and users' reactions. The report recommended that London should in the first instance implement a video-based road use charging system, until the results were available from the Demonstration of Interoperable Road User End-to-End Charging and Telematics Systems (DIRECTS) project [36], which would set standards for U.K. DSRC-based charging (see Section 8.7.5). In August 2002, Mayor Ken Livingstone gave the final approval to proceed toward a full-scale implementation of congestion charging in central London, using ANPR for enforcement.

If ANPR is used for enforcement, then there may be an opportunity to employ ANPR for video tolling, as described in Section 3.5.1.1. However, this apparently simple extension would still need to satisfy the benefit-cost arguments, may require additional roadside cameras at each charging point, would require new business processes and business rules, and would only be available for intermediate-use road users due to the need for manual checking before charges can be correctly allocated. Video tolling as a complement to DSRC OBUs and ANPR is used by the Melbourne City Link (Australia), the Cross-Israel Highway (Israel), and 407 ETR (Canada), and has been used on the Dulles Greenway, Virginia (United States).

There are currently no examples of video tolling in Europe for charging (with the exception of Bergen), although distance-based speed enforcement (known as section control) in the Netherlands relies on matching images captured at two separate locations to identify the same vehicle. Manual checking is still used to confirm speed offenses before enforcement action is taken.

3.5.5 Occasional Users

The vehicle rather than the user usually defines what is meant by an "occasional user." Access to the road network requires an alternate means of being charged, other than an OBU, for occasional users. In the future, it is likely that national road pricing schemes would be based on mandatory installation of OBUs regardless of the usage of the road network, in which case the definition of an occasional user becomes academic.

Section 3.5.1 outlined the economic case for developing different accounts when OBUs are not mandatory, some of which required OBUs to increase detection accuracy and to capitalize on the lower transaction costs that an automated charging process offers. It showed that the business case for OBUs (considering the operator and user costs) may not warrant that all users have an OBU-based account.

Section 3.2 identified the minimum requirements to enable a scheme to operate effectively, yet none of them specifically stated the need for an OBU; rather, it was stated that it should be possible to uniquely identify a vehicle and the road user's means of payment. ANPR can be used to read the vehicle's license plate number. However, the scalability of ANPR as an occasional user product is limited. Occasional users would need to preregister separately for multiple schemes, or the scheme operators would need to share preregistration details while meeting local data protection requirements. The handling of occasional users was regarded as technically and operationally complex in the 1990s, and, until the specific business process requirements were understood, presented a significant challenge.

The following sections outline the options available to operators of plaza-based schemes and open road schemes.

3.5.5.1 Plaza-Based Schemes

The main means of payment for occasional users for plaza-based schemes is cash, either paid to a toll officer or an ACM.

The greater the quantity of ETC-based vehicle passages, the fewer cash transactions are required, thus providing the opportunity to increasingly automate the toll collection process. As the quantity of ETC-based transactions increases, even if it varies by time of day, then the greater the opportunity to dedicate parts of the capacity of the toll plaza to ETC-only passages. There are three general approaches to the use of toll plazas, using approximate percentages of OBU usage:

- Less than 10% OBU penetration in local user population: Dedicated cash payment lanes, and mixed ETC/manual/ACM lanes for OBU-based account holders;
- From 10% to 20% OBU penetration in local user population: Cash payment in manual or ACM lanes, with ETC services in all lanes for OBU-account holders, including dedicated ETC lanes;
- From 20% to 60% OBU penetration in local user population: Cash payment in manual or ACM lanes adjacent to physically segregated express lanes or ORT lanes for OBU-account customers only.

3.5.5.2 Open Road Schemes

Examples of occasional user arrangements for nonplaza schemes are listed here.

- Melbourne City Link (Australia): *CityLink Pass* users register online or via a call center/IVR with vehicle license plate details and pay with a credit card or bank card. Each charge point is able to use ANPR to discard images from preregistered vehicles.

- LastKraft Wagen (LKW) truck tolling scheme (Germany): "Alternative user" terminals are located in truck stops and in other rest stops located at either side of the country's border. Transiting truck drivers or dispatchers are required to manually preregister a route at the roadside terminals, by contacting a call center or through the scheme operator's Internet site. Changes to the route can only be accommodated by reregistering.
- London Congestion Charging (United Kingdom): More than 5,000 retail outlets in the London area are supplemented by cash payment terminals in car parks.
- 407 ETR (Canada): No registration or prepayment is required. Vehicle is identified using ANPR, and the registered owner is identified and billed.
- Trondheim (Norway): ACMs were located in lay-bys at the toll ring, and not all entry points are manned. Over 90% penetration of OBU-based transactions occurs at peak hours. Toll collection services were completely removed on December 30, 2005, since the original purpose of the scheme, to fund road infrastructure development, had been satisfied. Ongoing road operational costs are now funded from the general taxation (see Section 8.4.1).
- Singapore ERP scheme: Installation of an OBU is mandatory for most Singapore-registered vehicles. Foreign road users planning to travel on ERP-priced roads can either get an OBU, also known as an in-vehicle unit (IVU), installed, temporarily rent a unit, or pay S$10 (approximately $6 or €5) for a daily license, regardless of the number of trips on an ERP-priced road.

The Austrian LKW truck tolling scheme offers no occasional user product. Road users of vehicles above 3.5 tons must acquire and install an OBU before using the national road network. This simplifies the business rules for enforcement, but places a greater burden on users. This also requires potential road users to be aware of the payment options, and how and where to acquire an OBU.

Other options may also be feasible where the primary means of charging is based on installation of an OBU by an accredited workshop. For example, a vehicle that does not meet the business rules based on total annual distance threshold could be regarded as occasional and therefore eligible for a simple user-installed OBU with limited automatic data collection capability. Although the installation cost would be significantly lower, the low-usage OBU would require greater effort from the road user to report usage, such as manually entering the start and end odometer readings. The data collection costs from the operating authority could also be greater in proportion.

3.6 Standards and Interoperability

3.6.1 Introduction

There are many examples where standardization has helped the competitive potential of an industry. A car tire can be bought with limited information, knowing that it will fit the wheels of a car. A GSM phone purchased in Hong Kong will function in Norway and the United States, and in any of the 860 networks and 220 countries worldwide [27]. A webcam acquired in Japan will work on a computer in Europe. The Internet Protocol (IP) can connect an FTP server in Indonesia to a client in Hungary. All this has been made possible through early cooperation between industry suppliers, leading to widespread distribution of highly differentiated, yet competitively priced products. From a user's perspective, not having to think about interoperability is a measure of the success of industry cooperation, regulatory guidance (where needed), and informed customers. However, there are many examples in which the same recipe has not led to globally interoperable products, yet consumer choice has not suffered (e.g., memory sticks for digital cameras, car entertainment systems, and electrical appliances).

There are two rules that have emerged for the selection and use of interoperable charging technologies:

1. Standards are necessary but not sufficient [37]. DSRC suppliers and road operators have shown that the variety of options defined by standards could mean that one DSRC technology uses a subset that is not compatible with another. The collective development of communication profiles, specifications, and test methods enables interoperability. This profiling is a necessary step beyond standards to enable ETC and road user charging in concentrated multiauthority road networks.
2. Multivendor interoperability may be desirable to lower the risk of technology supply and maintain ongoing competition, but the success of the scheme does not depend on it. One of the world's largest ETC schemes (measured by revenue collected) is EZ-Pass, offered by operators in the Northeast United States; it uses a single charging technology vendor. Back-office interoperability was enabled through standardizing the transaction records exchanged between operators.

Regions that aim to attract private finance to upgrade highways and infrastructure have more confidence in implementing charging if they know that specifying standards-compliant products simplifies the initial procurement, while multivendor interoperability reduces long-term procurement and operating risks. The benefits of standards and interoperability are applicable to all charging technologies, as discussed in Section 3.6.2 and 3.6.3. There may also be disadvantages if the development of standards adds delays and introduces technology development risk. This often means that debugged standards are coopted from one country to another country, since the development of a new standard for local use may make local projects less attractive to potential bidders. The alternative, with the caveats stated above, is to procure a proprietary solution, although with the significant efforts invested in standards development, this need not always be an option.

3.6.2 The Benefits of Standards

Standards designed specifically for ETC and road user charging have generally focused on the connection between in-vehicle equipment and the roadside. There is little evidence, to date, of application-specific standards being applied to enforcement, other than generally accepted methods for image format, encryption, and compression methods to maintain the integrity of evidential records.

The European Committee for Standardisation (Comité Européen de Normalisation, CEN) and its Technical Committee on Road Transport and Traffic Telematics (TC278) initiated one of the earliest standardization activities in 1991. In Spring 2004 (almost 13 years later), the completed standards defined the operation of the DSRC interface between an OBU and a roadside system. The standard is applicable to all members of CEN, including the national standards bodies of all EU member states and the European Free Trade Area (EFTA), leaving institutional barriers as the final hurdle to enable multinational interoperability.

U.S.-developed standards include Caltrans' Title 21 [38] and ASTM E2158-01 [39] for DSRC technologies in the 902-to-928-MHz band. Since the Federal Communications Commission (FCC) announced the availability of the 5.9-GHz band in October 1999, ASTM and IEEE have been developing complementary standards for vehicle-roadside communication, beginning with ASTM E2213-02 [40] in 2002 for layers 1 and 2 of the OSI model of network architecture. ASTM and IEEE are currently working on the upper OSI layers, as described in Section 3.5.2.1.

Competition for ETC projects has introduced CEN DSRC–compliant solutions in Southeast Asia, South America, and South Africa. However, CEN-compliant products do not have a market monopoly. Proprietary solutions and systems that comply with standards created in the United States and, to a lesser extent, Japan, are also being used outside Europe and the United States.

CN/GNSS generally relies on standard-bearers such as GPRS for communication of road usage information, map database updates, and tariff tables, depending on whether a thin or intelligent client is employed. Locally applicable DSRC standards and specifications apply where a CN/GNSS OBU relies on DSRC for localized communications for enforcement. Consequently, current activities are focused on the application level to ensure interoperability, as discussed in Section 3.6.3.

3.6.3 The Benefits of Interoperability

The benefits of interoperability are often treated as purely technical. The commercial benefits are far more important and include:

- Creation of multiple supply chains from multiple vendors, potentially reducing procurement risk and threat of monopoly pricing;
- Ease of technology comparison by highway operators, reducing the need to focus on technical elements, and simplifying procurement;
- Separation of infrastructure procurement (i.e., high-cost, low-volume lane equipment) from OBU procurement (i.e., low-cost, high-volume OBUs), simplifying procurement;
- Continuous competition for infrastructure expansion and new OBU business, delivering lowest cost and greatest benefits to the highway operator;

- Geographic expansion from multiple road operators without the need for coordination in technology selection, reducing procurement complexity, and simplifying expansion;
- Increased user choices among OBU supply chains, with potential for direct sales to highway users by third party outlets.

Ensuring interoperability across state or national borders with an OBU that meets minimum interoperability requirements means that road usage records (GNSS) or transaction records (DSRC) will be in a form that permits charge reconciliation between operators (or payment service providers). This ensures that road users benefit from OBU roaming, trip flexibility, continuous service provision, and a single bill, just as cellular mobile service providers routinely deliver to their customers.

Enabling cross-border usage of an OBU that complies with technical interoperability requirements depends simply on the principles of contractual interoperability, as is evident from bilateral agreements between Austria and Switzerland (currently only one-way), Denmark and Sweden, Spain and Portugal, and between other pairs of EU and European Economic Area (EEA) member states.

Increased cooperation between highway operators supported by existing standards (initially DSRC-related) has meant a power shift from suppliers to highway operators. In Europe, operator involvement in CEN TC278 was virtually nonexistent before the prEN (draft) stage of European standards. During this period, the GSS [41], A1 [42], and A1+ [43] (on board charging extension to A1) interoperability specifications were created to provide a simplified approach to specifying a useable subset of transactions, which ensured a minimum service level interoperability between different vendors' products.

However, the most prominent European interoperability programs, such as TIS (France) and the Common EFC System for Road Tolling European System [44], have been entirely driven, since 1999, by highway operators that invited DSRC vendors to participate. In addition, the Concerted Action for Research on Demand Management in Europe (CARDME) [45], DIRECTS (United Kingdom), PISTA, and the development of the WAVE Platform within the U.S. DOT–led vehicle infrastructure integration program, are all examples of interoperability initiatives also driven by highway owners and national administrations.

Nevertheless, we can already see the benefits. The first pioneering applications of ETC were initially driven by highly localized needs, and it took almost 10 years from the first use of ETC until cross-border interoperability found its way onto the agenda. In Europe, the directives that enable lorry road user charging (LRUC), and the modified directive relating to interoperability, have increased industry debate, helped form national technology preferences, and established positive support for cross-border interoperability. This process took only 5 years. By comparison, this was also the time required for Switzerland and Austria to plan, deploy, and launch national schemes.

An operator is now able to routinely procure DSRC roadside systems, OBUs, and turnkey systems from several competitive vendors. Multivendor sourcing requires standards-compliance, supported by a debugged interoperability specification. The benefit of interoperability for small-scale isolated schemes may be less important, so standards-compliance is less critical. As earlier described, the U.S. EZ-Pass, ETR 407 (Canada), and the Singapore ERP scheme are based entirely on proprietary charging technologies, although all were procured when standards-compliant products were not generally available.

Once a scheme is operational with charging technology that complies with standards and an interoperability specification, then future OBU procurements can be routinely separated from main system purchase, although many buyers have continued to depend on significant technical knowledge to ensure that vendor products comply with the local requirements for interoperability. Notably, the Chilean Ministry of Public Works (MOP) appointed the Germany-headquartered TÜV to verify OBU compliance to a local interoperability specification underpinned by CEN DSRC standards [46–49]. Similar interoperability specifications based on the same set of standards have been produced in Australia [50], Brazil [51], Chile [52, 53], Norway [54], and Sweden [55]. The French *Liber-t* project requires that all OBU and roadside systems pass a formal site acceptance test, managed by the L'Association des Sociétés Françaises d'Autoroutes et d'Ouvrages à Péage (ASFA). Standards backed by interoperability specifications, published test methods, operator-specific tests, and a willingness for scheme operators to enter into contractual arrangements are critical to ensuring a seamless user experience when roaming. The ultimate goal in Europe is the enabling of a road user to use a single OBU to travel on all charged road networks within the European Union, with few exceptions. The road user would only have to register with one organization (a payment service provider), and receive only one bill [56, 57].

The U.K. Department for Transport embarked on a program to develop a national specification for interoperable payment of road use charges, consistent with European standards and potentially enabling compliance with the European Interoperability Directive. The U.K. DIRECTS project [36], using 500 or so volunteer drivers with vehicles equipped for a trial in Leeds in the North of England, demonstrated an end-to-end solution for DSRC-based charging. The DIRECTS project is presented in Chapter 8, on international case studies.

Looking globally, ISO 17575 "provide[s] a framework for achieving interoperability between different EFC systems using satellite positioning and cellular networks and define[s] in particular a framework for on-board equipment to roam between different EFC services, even where the EFC services have different policies and charge structures" [58] applicable globally. In Europe, the Minimum Interoperability Specification for Tolling on European Roads (MISTER) initiative builds on this to guarantee technical and procedural interoperability, consistent with the aims of the European Electronic Toll Service (EETS), discussed further in Section 8.5.1.

One of the most prominent projects that aims to develop a media-independent vehicle-roadside communications approach is CALM, led by ISO/TC204 Working Group 16. It is expected that the interfaces will include DSRC (IR and microwave), millimeter wave at 63 GHz, mobile wireless broadband, GSM, and UMTS services, as a minimum. CALM will define handover mechanisms between multiple media providers to ensure service continuity that is completely transparent to the user. The multimedia expectation requires coordination with other standards bodies, including the European Telecommunications Standards Institute (ETSI) (TG37 car-to-car communications), and the Wi-Max Forum. A common global allocation of bandwidth will also need the cooperation of the International Telecommunication Union (ITU) and the Conférence Européene des administrations des Postes et des Telecommunications (CEPT), plus local spectrum regulatory bodies, such as the FCC. Further information on CALM is given in Section 9.2.5.

3.7 The Future

3.7.1 Introduction

The dominant charging policy for road use was toll collection up until the mid-1990s. This led to the emergence of products aimed primarily at ETC. Since then, new policies have evolved, and technology vendors have developed adaptations of well-understood technologies (e.g., IR, ANPR, and CN/GNSS) to meet these new policy requirements.

The future evolution of the RUC market as a whole is addressed below, based on observations of relevant global trends, market forces, and a statement of possible future scenarios. Regulatory influences are treated separately.

The most important influence on the use of charging technology and the network of technology suppliers and supported integrators continues to be infrastructure expansion driven by economic growth. "National and local Government initiatives, as well as an increasing user requirement for more convenient tolling, are the key factors driving demand for ETC systems" [59]. A shortfall in public funds and investment in highway infrastructure upgrading is also leading to growth in build, operate, and transfer (BOT) projects and commercialization of existing highways. Increased awareness of the adverse impact of economic activity on the environment, particularly among OECD nations, has led to increased political and institutional support for pay-as-you-go principles. Finally, contributors to congestion, such as population growth, increased vehicle ownership, and increased vehicle miles traveled (VMT), highlight the need for balance between capacity expansion and efficient use of existing capacity. There are highway instrumentation, telematics, and RUC solutions for either approach.

The global trends and regulatory influences described above were used to assess possible market evolution. Reports published in Brazil, Japan, and the United States describe the rapid expected growth in ETC usage:

- The private investments in concessions "have been the main factor behind the adoption of ITS in the Mercado Común del Sur (MERCOSUR) region (South American trading bloc). Because of this, the most common ITS application in the region is for highways, as in ETC and highway communication systems" [60].
- The U.S. national intelligent transportation systems program sets out a plan that ". . . advances the safety, efficiency and security of the surface transportation system, provide increased access to transportation services and reduce fuel consumption and environmental impact and [the introduction of] a single payment medium for regional and national travel" [61].
- ASECAP states that ". . . the axes that will define the future road policies that will impact its members (highway operators) include a new Infrastructure

financing framework, a common methodology for the infrastructure charging, RUC interoperability (DSRC—GPS/GSM-GALILEO), policies that differentiate between private cars and heavy lorries and between urban areas and motorways" [62].

- ITS Japan claimed recently that "It has been calculated that [the planned investment] will allow about 80 percent of total traffic on toll roads to move without stopping. In future, all toll gate booths will be fitted with a card reader capable of reading the electrically transmitted information of the IC card inserted in the on-board equipment, enabling every vehicle fitted with ETC on-board equipment to use all toll gates in the country" [63].

Other external forces that impact RUC technology developments include global decisions on radio spectrum allocation, the prominence given to large-scale projects such as Galileo, and regulatory forces at the regional and national level. The evolution of the RUC industry is also guided by forces from several directions, including: continued investment in applications trials with community funds (e.g., the Fifth Framework Programme in EU member states); technology transfer initiatives (i.e., long-term net shift of defense to civilian expenditures); infant industry protection measures through the imposition of import tariffs; and local technology transfer provisions (e.g., China and Brazil).

3.7.2 Future Scenarios

Table 3.4 describes a policy-led future scenario.

If we adopt the perspective that charging for road use is simply an application, then we have the scenario in which road user charging and tolling would reside alongside other in-vehicle applications, such as navigation, safety enhancement, and information systems. These applications are fed by sensor inputs, providing vehicle position, speed, vehicle-to-roadside communications, object detection, and other active and passive detection and measurement systems. Sensor inputs may feed one or more applications, so information sharing may drive applications to coexist on the same vehicle platform. For example, if the vehicle is equipped with more advanced methods of determining road user charges based on distance traveled, then the OBU that was adequate for interoperable charging now needs to have greater connectivity with the vehicle to be able to securely access distance traveled information. Economies of scale, security, and common information needs

Table 3.4 A Policy-Led Future Scenario

Technologies will continue to evolve as the acceptability of tolling and road user charging increases, as the complexity of charging policies increase, and as road users have increased contact with different charging policies. Many users will initially come into contact with the technology by paying a charge electronically. These users will experience technology at its most focused level: usually no more than a user-installed OBU that beeps to indicate that a transaction was performed successfully. In the long term, vehicle manufacturers will provide interfaces to retrofit devices before offering an integrated solution. Users will interact with the scheme through an intermediate service provider with whom the user has an account. The user will be able to prepay or postpay, depending on status, through a variety of channels targeted at specific user groups.

further suggest that road user charging and tolling could assume the status of an embedded application within the vehicle. This is discussed further in Section 9.3.2.

It is easy to predict complex technology scenarios where the technologies for road user charging need to encompass all possible sensor inputs to serve all possible charging policies that a user may experience in a typical journey. However, ensuring interoperability between geographic areas or road segments that have different charging policies (e.g., tolling, area pricing, cordon pricing) can be seen from three different perspectives, discussed in the following.

3.7.2.1 Home Policy Compliant

Home policy compliant relates to isolated, region-specific procurements. A user registered with one scheme would need to act as an occasional user with the other scheme. A heavy goods vehicle with a CN/GNSS/DSRC OBU would need to pay cash or register as an occasional user elsewhere. Extrapolating this scenario to the future, a gradual increase in the number of bilateral interoperator agreements would result in vehicles meeting minimum technical interoperability requirements for the bilateral agreement operators but not all regional road charging operators. The burden rests with the road user to ensure that the payment means is acceptable outside the home area.

3.7.2.2 Minimum Policy Interoperability

A more desirable outcome of the focused, home policy compliant would be where all road operators support a minimum common charging policy. For example, an OBU issued by one operator would be accepted as a valid means of recording and reporting road usage to all operators on whose infrastructure the user travels. A user registered for scheme A can participate as an occasional user in scheme B using scheme A technology. In other words, the technology issued by operator A is accepted as valid technology for occasional users on operator B’s infrastructure. If the reverse also applied, then true bidirectional interoperability would be achieved, and users having either technology would be able to use either infrastructure without additional registration.

This policy is analogous to a cellular phone subscriber having a broad choice of handsets, each with different capabilities, some of which may or may not be supported when roaming (e.g., instant messaging, streaming video). However, every operator’s network supports the minimum capability (e.g., voice and data).

3.7.2.3 Full Policy Roaming

This scenario states that meeting the requirements for minimum interoperability for all road operators would require a maximum capability OBU. This has no analogy in mass-market cellular communications.

This scenario would only apply if an OBU needs to meet the charging policy requirements of the operator with the most complex charging policy within the area in which the user could reasonably be expected to travel. For example, operator A would need to accept vehicles equipped with charging technology from operator B that have the capability of measuring road usage based on a multilevel, time-of-day, distance-based charging mechanism as employed by operator B. In this case, minimum interoperability means that a more capable OBU would be required, incorporating many charging technologies.

The most likely technology future will be dictated by legislative requirements, the propensity of road operators to agree on occasional user schemes, technology costs that can be borne by the road user, and the relative penetration rate of each technology choice in a retrofit and new vehicle market.

One possible impact on the course of technology development to 2010 of full policy roaming is described in Table 3.5. As earlier, this is not a forecast, but merely one of many possible future outcomes of regulatory, institutional, and technology development activities.

The integrated scenario is only applicable where the convergence of procurements, cross-border interoperability, and economies of scale drive cooperation and the emergence of new organizations dedicated to increasingly specialized parts of the road user charging and tolling value chain. Many vertically integrated scheme operators may focus on core operations, while road users benefit from a choice of payment service providers and mass customized options for payment of road user charges. Integration with other ITS services may also be possible (e.g., Japan and VII case studies in Chapter 8), including traffic information services, safety-related devices, and automatic payment for fuel and parking.

Table 3.5 Integrated Scenario

Development of hybrid OBUs supporting GNSS/CN and DSRC, where DSRC is the lowest common denominator for complex and monolithic OBUs to ensure interoperability in EU/EEA, including newly joined EU member states;
Continued routine use of DSRC technologies for highly focused, mass market applications, such as ETC;
Continued development of contractual interoperability to ensure coexistence with other forms of EFC, such as CN/GNSS and ANPR (already introduced as nationally or locally);
Evolution of charging policies from only highways towards all roads, with local differentiation based on emissions class, classification, axle weight, time-of-day, and measured congestion;
Emergence of cross-border charge clearing services, and service providers driven by economies of scale;
Further development of regional [EU, EEA and North American Free Trade Agreement (NAFTA)] contractual roaming agreements;
Broad acceptance of road user charging policies within vehicle and transport services supply chains (e.g., retrofit outlets, vehicle manufacturer options);
The development of multimode, flexible OBUs, adaptable to local RUC service requirements;
Development of pan-EU cross-border enforcement processes [e.g., based on Video Enforcement for Road Authorities (VERA)-type tools and equipment approvals], initially on a bilateral basis;
Cooperative operator-driven procurements for RUC systems;
Continued emergence of OBU-only vendors;
Scheme overlap, separating the roles of OBU issuing, account management, and RUC service provision.

Source: [64].

3.8 Summary and Conclusions

A technology perspective on tolling and road user charging reveals a long list of technology building blocks that can be combined to meet functional requirements defined by charging policies. The optimal mix of GPS and DSRC systems will be determined by national charging policies, and minimum interoperability requirements for travel on networks of regional roads that have different policies for charging and enforcement.

The choice between having or not having an OBU will depend on regulation (i.e., mandatory or voluntary installation), and the business case for scheme operators to encourage the use of OBU-based accounts by different usage categories of road users. Regulation and interoperability will blur the choice between DSRC and GNSS/CN toward OBUs that embody all technologies. We have seen that DSRC, as a technology building block, has been widely adopted for ETC. However, the introduction of distance-based charging schemes, initially for heavy goods vehicles, has already challenged the business case for discrete detection methods offered by DSRC, to also include methods that are applicable to all roads with multiple tariff boundaries. The development of increasingly accurate and reliable satellite positioning methods that depend on different forms of augmentation will increase the global applicability of CN/GNSS schemes. Regulatory pressure for distance-based charging is essential for the availability of positioning information to an OBU, whether delivered by DSRC or satellite positioning. The drive toward interoperability, underpinned by standards, will enable OBUs to roam between areas that differ in charging policy, which requires the OBUs to be capable of providing road usage information to satisfy local scheme rules. The pressure on OBUs to evolve to more sophisticated forms could be mitigated by the evolution of central systems. Chapter 6 shows that interoperability does not always require the charging technologies to meet the requirements of all schemes. Unless all schemes have the same approach and have coordinated their procurements, it is likely that the central systems should also be regarded as a critical enabler of interoperability, rather than an exclusive focus on charging technologies.

Regional solutions (defined by an economic area, such as the EU or NAFTA) will remain feasible in the future. Wide area augmentation methods and regional standards for wireless communications suggest that road user charging technologies will need to be bundled to meet regional requirements. Similarly, DSRC and ANPR provide baseline capabilities for enforcement; DSRC can interrogate OBUs to check account validity and other declarations; and ANPR allows the handling of evidential images to be highly automated. Within the confines of each scheme, ANPR also allows occasional users to be registered. For higher frequency road usage that does not warrant an OBU, the use of video tolling can reduce transaction costs for pay-per-use operations.

The common threads of RUC technology development are the continued drive towards interoperability at all levels, from technical to contractual; the trend to road use charging and tolls; and the need to find new sources of investment for infrastructure upgrade and expansion, mitigated by the institutional and organizational hurdles that need to be overcome.

Regulation is also expected to continue its impact on the development of RUC technologies. The greatest influence on the technology choice for a vehicle owner, driver, local authority, and highway operator will depend on the regulatory environment and the local or national charging policies. Distance-based charging will require discrete or continuous vehicle positioning or distance measurement capability. Toll roads will continue to maintain highly localized collection and enforcement schemes to meet long-term concession targets, but will also be under pressure to cooperate with other distance-based policies.

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