

CONGESTION CHARGING MECHANISMS FOR ROADS, PART II – CASE STUDIES¹

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This is Part II of Hau (2006a, *Transportmetrica*, 2, 87-116) on evaluating congestion charging mechanisms for roads. With the conceptual framework developed in Part I, this paper presents several case studies of congestion charging methods that are used in practice.

KEYWORDS: Congestion externality, congestion charging, electronic road pricing, congestion tolling, charging technology

1. INTRODUCTION

Part I develops the criteria for a ‘good’ road pricing system from a user’s, road authority’s and society’s point of view, as given in Hau (2006a, Section 2.1). Having considered the major direct and indirect instruments of charging for congestion in Hau (2006a), I present several case studies of congestion charging methods that are used in practice. Direct charging could be broadly categorized as off-vehicle recording versus on-vehicle metering. With off-vehicle recording, as with telephone, gas and electricity charges, the actual charging is monitored off the vehicle even though a transponder may be placed on the vehicle itself in the case of automatic scanning. On the other hand, with on-vehicle metering, actual charges are registered on the vehicle itself using automatic meters -- similar to the concept of taxi meters and (stored value) phone cards. All of the off-vehicle recording methods are based on point pricing whereas on-vehicle metering methods involve either point pricing or continuous pricing. Point pricing refers to the pricing of a vehicle when it passes a charging point such as a toll site. Continuous pricing, on the other hand, involves clocking a vehicle for the time spent or distance covered between two charging points.

2. OFF-VEHICLE RECORDING

Within the off-vehicle recording category are three instruments: 1) manual charging by admissions fee via tollgates and reserved lanes; 2) automatic scanning via automatic vehicle identification (AVI) technology, otherwise known as electronic toll collection (ETC) or euphemistically called electronic toll and traffic management (ETTM); and 3) a combination of manual and automatic scanning of vehicles. Manual and/or electronic toll collection involve point pricing and hence are less costly to operate than continuous pricing methods.

¹ This paper is based on Timothy D. Hau (1992b) Congestion Charging Mechanisms for Roads: An Evaluation of Current Practice, World Bank Policy Research Working Paper Series, WPS 1071, World Bank, Washington D.C., pp. 1-99. The economic fundamentals of road pricing are discussed in Hau (1992a, 1998, 2005a,b).

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2.1 Manual charging via tollgates

The first mechanism to consider is the use of manual tollgates. This is an established and well-known technology, administratively straightforward, publicly accepted for toll roads, bridges and tunnels, as well as politically palatable. However, manual charging results in low throughput, with about 350-400 vehicles per hour for a toll lane (Hartje, 1991; Ardekani, 1991). In contrast to supplementary licensing, in which systems costs are relatively low and user costs are also low because of its nonstop nature, the setting up of tollgates requires significant capital investments in toll plazas and toll collection facilities. In order to cater to the typical need for two to three approaching toll lanes to conservatively serve every expressway lane (as in the United States (Seila and Wilson, 1991)), toll plazas require large plots of open space, not often found in urban areas.³ The construction cost of toll lanes (and tollbooths) and land acquisition costs are all fairly high in major conurbations. The operating cost is nontrivial because it is heavily driven by toll operators' salaries. Based on a sample of six mainline/ramp barrier systems, the toll collection cost per transaction ranges from US\$3.6 cents to US\$7.5 cents in 1983 (Wustefeld, 1988, Table 5).⁴

The tollgate method of direct charging is akin to supplementary licensing if one is considering a simple zone, and is therefore able to tackle the problem of through traffic not captured by the instrument of parking charges, for instance. However, manual charging imposes more externalities than it attempts to internalize by requiring that all vehicles come to a full stop to elicit payment, creating long queues and waiting times inevitably. The stop-and-go traffic results in increased travel time and operating costs (in the form of fuel and vehicle wear and tear). Besides being particularly susceptible to these costs, heavy vehicles also create severe road damages as a result of stopping and starting. In general, less attention has been paid to the increased risk of accidents and pollution levels at toll plazas. Other problems have been encountered, such as the lack of financial control of toll box revenues. Scandals periodically arise in which toll operators embezzle cash cages. The need to physically transfer large amounts of coins is another problem.

Besides the manual operation of tollbooths, automatic coin machines and hoppers for exact change are also used to save on personnel costs; automatic coin machines marginally improve the throughput to about 400 vehicles per hour for a toll lane. The disadvantage of these machines is that they still require vehicles to come to a stop. Note that six approach toll lanes are required to serve one expressway lane in order to ensure that the capacity of the road itself is not constricted by the capacity of the tollbooths.⁵ This suggests that tollbooths could be designed in a way that does not disrupt traffic, but manual charging would involve unacceptably high set-up and operating costs relative to other mechanisms. One minor disadvantage of using automatic coin machines is that charging for one type of vehicle is only applicable on a per lane basis, unless different vehicle types are designated to use specific toll lanes, which would decrease the capacity of the toll booths and increase the complexity of the charging instrument.

³ Small wonder the Smeed Report (Ministry of Transport, 1964) dismisses this approach to curtail congestion in a mere couple of sentences.

⁴ These figures are based on toll facilities which have lanes for both manual operation and automatic coin machines.

⁵ I am indebted to Richard Scurfield for clarifying these points.

Another form of charging is with the use of coupon books. They have similar advantages to automatic coin machines but the printing cost is not insignificant. Similarly, problems of fraud occur. (The magnetic card method of running magnetically-stripped cards, such as credit cards, through a mechanical reader may help control operator fraud, but would be the slowest and least practical method of all.) Based on a sample of five ticket system toll roads, the cost per transaction ranges from US18.4 cents to US42.4 cents in 1986 (Wustefeld, 1988, Table 6).

Perhaps the irony of using the tollgate approach to tackling congestion can be expressed as follows: if an urban area is congested, then the planner ought not add to the congestion externality the non-negligible cost of transaction itself. At the other extreme, if the facility is uncongested, then the planner should not impose a charge since the incremental congestion cost is nil.

From a financial point of view, if the system is installed for a long period of time, the large capital costs of toll plazas could also be amortized over more years. Thus, from an operator's perspective, this system is more amenable for a long-term demonstration or experiment rather than a short-term one (Bhatt, 1974). If so, the long-run cost per transaction is a valid index for analyzing the cost-effectiveness of alternative charging instruments -- assuming that the aim is to curtail one (socially wasteful) trip.

It would be a relatively simple matter to implement cordon pricing using manual tollbooths with just one single zone. However, urban areas seldom have the necessary space for two (or more) suitably designed cordons manned with tollbooths to implement multi-zonal, cordon-based pricing. As such, this method is inferior to the ALS method of cordon pricing because it impedes traffic. Like the ALS, since charging on a continuous basis (by time or distance) is impractical, the charging basis is done via point pricing, i.e., by crossing a gantry point. Unless pricing gradations are fine enough (which as we have discussed is infeasible with the tollgate collection mechanism), boundary problems would arise with vehicles slowing down or even parking outside a zone boundary just prior to a change in the period of operation, similar to problems with ALS. Once inside the zone, however, there is an incentive for additional mileage to be undertaken, adding to congestion. The prime example of cordon pricing which utilizes manual tollgates is that of the Bergen Toll Ring, in operation since January 1986 (see Appendix 1).

Under what circumstances are tollbooths acceptable as an instrument of charging for congestion? Only if: i) the number of entry and exit points is limited, and ii) the capacity of the road is not greatly constrained by the capacity of the toll collection facility itself. When equipped with a minimal number of toll lanes to reduce transactions delay, the few entry points to the urban area could also result in tolerable capital and operating costs. With this method, it is desirable to establish reserved lanes for those with seasonal passes (as was done in Bergen) to maintain nonstop traffic through the tollgates as well as to limit personnel costs. As traffic growth increases along trend and the net benefits of curtailing congestion rise, the setup of the reserved lanes is ideally suited for the conversion to electronic subscriber ones (which charge on a *per trip* basis), as was done in Oslo following a trial period of using seasonal passes.

2.2 Automatic scanning via automatic vehicle identification

The second mechanism of directly charging for congestion on an off-vehicle recording basis is automatic scanning via automatic vehicle identification (AVI). As with manual charging, this is considered point pricing as vehicles are charged when they pass a reader known as an interrogator. The third mechanism under the rubric of charging for

congestion by direct methods by registering charges off the vehicles is simply a combination of manual and automatic charging. Since the basic technology for automatic road use charging has been thoroughly tested and used on toll roads, tunnels and bridges, I shall first discuss the pros and cons of electronic toll collection (ETC) using AVI in such open environments and then discuss its application and extension to road pricing within a city-wide context.

2.2.1 AVI technology

Automatic vehicle identification (AVI) refers to the automatic identification of vehicles in motion. The term ‘automatic vehicle identification’ is a bit of a misnomer since it is the transponder located in the vehicle rather than the vehicle itself that is ‘identified’ (Thomson, 1990). Thus the less evocative term of ‘electronic toll and traffic management (ETTM)’ became popular. Historically, AVI was first developed and tested in the 1950s and the early 1960s (Vickrey, 1960; Ministry of Transport, 1964; Catling, 1987). The Port Authority of New York and New Jersey supported the development of AVI technology as early as 1963 (Foote, 1981). In fact, it was upon the instigation of the American Association of Railroads that AVI technology was originally pioneered in the early 1960s for the purpose of tracking railroad boxcars. AVI technology is now widely used in rail transportation and intermodal transportation.

Schematically, AVI consists of three functional elements: a transponder (known as a ‘tag’) which stores a unique identification code; an interrogator which ‘reads’ a transponder and decodes its identification; and a computer system which transmits, analyzes and stores data (Davies, 1989; Sommerville, 1991). There are four broad types of AVI technology:

- Optical and infra-red systems
- Inductive loop systems
- Radio frequency and microwave systems (including surface acoustic wave technology)
- Smart card systems

One of the earliest generations of AVI technology involves optical means (Davies, 1989; Sommerville, 1991).⁶ It is not unlike bar code scanning available in grocery store checkstands (which are not close to being considered fully reliable). With optical systems, the coded labels are placed outside the vehicle. A laser beam from an optical scanner tracks the bar code sticker placed on side windows and analyzes the reflected light. However, this technology becomes less reliable under conditions of poor visibility (e.g., when there is dirt, snow, ice, rain or fog). Further, counterfeiting of bar codes is easily carried out and a vehicle’s speed is lowered when attempting to meet the exacting requirements imposed by optical systems. Computer scanning of vehicle number plates was tried out on some French toll roads but had not reached a tolerably low error rate in readability in the early 1990s. In the 1970s, infra-red technology based on similar

⁶ Optical-based automatic car identification (ACI) is still used in some nonroad-based transportation environments, as exemplified by the Washington Metro’s use of ACI since 1976 (Armstrong, 1984).

principles of operation as the optical-based ones also floundered when subjected to poor environmental conditions.⁷

A second type of AVI technology is the inductive loop system, which operates like a conventional traffic detection and counting loop mechanism embedded in the road pavement (Davies, 1987; Catling, 1987). Since an inductive loop system operates at frequencies between 50 and 500 KHz, it can also be regarded as a low radio frequency system. Operationally, an antenna loop situated in the pavement communicates with a transponder mounted underneath a moving vehicle. Basically, there are three types of systems: active, semi-active and passive. The active system derives its power from the motor vehicle's power supply itself. Since the electronic transponders are powered externally in an active system, the security of the system may be vulnerable to external interference inadvertently. A passive transponder is one which is energized when the vehicle passes a power loop buried beneath the road surface. In response to being activated, the transponder's identification code is decoded and returned to receiver loops embedded in the road, which in turn transmits the information to a computer for data processing. Tests carried out by California's Department of Transportation confirm the known fact that the performance of inductive loop systems is adversely affected by steel-reinforced pavements (Davies, 1989). While free of the aforementioned shortcomings of an active system, a passive transponder's principal disadvantage is the limited field length within which it could be triggered and operated.⁸ Thus, a technological development which aimed at overcoming the shortcomings of both systems involves the production of a semi-active transponder with an internal lithium battery which yields greater operating distance as well as relatively long life. Active inductive loop systems

⁷ Automatic or electronic route guidance, which does not require very stringent requirements of reliability, uses a more advanced infra-red technology based on a dynamic two-way communications between an in-vehicle unit and a roadside beacon. Static route guidance uses self-contained, mapping information stored in a vehicle only, whereas dynamic route guidance obtains digital map information and routing recommendations both aurally and visually. The latter manages traffic flow by using road-side infra-red beacons to transmit and receive dynamic data to all moving vehicles in (almost) real time (Catling, 1990). Siemens' Euro-scout system -- the latest generation of the ali-scout system -- has been in full scale field trial in Berlin for at least four years. GEC's Autoguide system has been tested on an experimental basis since early 1988 in London and a commercial system is expected to be available in 1993 (Catling et al., 1991; Belcher and Catling, 1987). The United Kingdom's Transport and Road Research Laboratory (TRRL) estimates that Autoguide users could achieve average travel time savings of around 10% and a reduction of distance driven of 6% (Department of Transport, 1988). On the other hand, because traffic is already around capacity level during peak periods, a slight decrease in traffic, as a result of diverted traffic, results in significant savings of £125 million per year for London (assuming only 400,000 users out of 3 million registered vehicles subscribe to Autoguide). The cost of the *pilot* stage ranges from £5 - £10 million in 1988 figures. It is also estimated that the benefits of a dynamic route guidance system are substantial at about £800 million per year in the UK alone and over £4000 million per year for Europe (Jeffrey, 1987). The economic benefits are broken down as savings in direct fuel cost (15%), savings in operating costs (40%) and savings in travel time (45%). In the United States, the Federal Highway Administration is comparing the benefits of different route guidance schemes such as Pathfinder as part of the Intelligent Vehicle Highway Systems (IVHS). It is recommended that automatic road user charging systems be designed to be compatible with route guidance systems in future *Dedicated Road and In-Vehicle Safety (DRIVE)* projects in Europe (Catling, 1990).

⁸ A prime example of an inductive loop system is the AVI system which was thoroughly tested for the Hong Kong Electronic Road Pricing Scheme. It uses a transponder of the passive type -- known as an electronic number plate (ENP) -- which contains standard and proprietary integrated circuits and several ferrite aeriels for receiving and transmitting signals. Developed by Plessey Controls Ltd., the ENP is about the size of video-cassette tape, weighs 1.2 kg [2.6 lb], and would be permanently installed on a vehicle's underside, fully deserving the designation of 'automatic vehicle identification'.

have been used for automatic bus identification in the United States, Europe and Australia (Catling, 1987).

Radio frequency (RF) transmission (otherwise known as high RF or microwave technology) forms the third and presently most popular type of AVI technology. The system is modular and the radio frequency transmissions span the officially-approved KHz, MHz and GHz ranges. Because of the higher frequency, more data can be packed and transmitted back and forth via RF technology, which is vital to enhancing system security. At the same time, lower operating wavelengths of microwave systems result in the manufacturing of a smaller and lightweight transponder that can be easily slipped into someone's shirt pocket and thus made transferable from vehicle to vehicle without any difficulty. Just as with inductive loop systems, there are three types of transponders with microwave systems, namely active, semi-active and passive transponders, and the same qualifications apply to them. Further, with microwave technology, a high frequency level is needed for use with a nonbattery powered tag, which could potentially pose a health hazard, at least psychologically.⁹ Thus a semi-active tag appears to possess the advantages of being able to transmit large amounts of information in a very short time and over a relatively longer operating distance. In addition, a semi-active tag can keep the power transmission level of microwave antenna-readers at tolerably low levels.

Surface acoustic wave (SAW) technology is yet another developed radio frequency-based AVI system (Sommerville, 1991).¹⁰ Application of the RF technology is widely used on those toll roads in the United States which utilize AVI technology, whereas SAW technology is used on toll roads equipped with AVI in Norway. For the most part, microwave technology appears to have superseded AVI technology based on optical and infra-red means. It involves no action on the part of the motorist: he or she simply buys or leases an electronic tag and places it behind the windscreen or the rearview mirror using attachments such as velcro pads, letting the electronics automatically charge for toll crossings. Since many of the transponders operational on toll roads are of the passive and read-only type, they are (thick) credit card-sized and they are removable. Such a transponder electronically communicates its encrypted identification code with roadside readers via high frequency radio waves.¹¹

How does the system work? A vehicle is driven past a pricing point nonstop at high speeds (up to a maximum speed of 300 kph [180 mph] in principle). An antenna -- connected to a reader -- is placed by a signpost (or mounted above on a gantry) and

⁹ An example of radio frequency AVI technology is US-based Amtech Systems Corp.'s TollTag®. Amtech's passive tag (priced at US\$32.25 a tag in 1992) involves one-way communication, weighs 40 gm [1.4 oz] and operates at the reserved frequency of 915 MHz (with a range from 850 to 950 MHz) and possesses a maximum field length of 9 meters [30 ft]. A heavy duty Amtech transportation tag weighs four times more and operates at 915 MHz as well as 2.45 GHz (with a range from 2.4 to 2.5 GHz) -- the frequency at which the industry aims to standardize at. The three major frequency bands used are 880 MHz, 915 MHz and 2450 MHz. In Spring 1992, Amtech came up with the IntelliTag™, which uses the same "modulated backscatter" reflective technology. Priced at around US\$40 a tag in large quantities or US\$49.50 a tag, the two-way communication link provides for 240 bits of fixed and variable data storage space (such as time and date stamp, account balance, etc.) on the transponder. These features allow for read-write transactions that are fully capable of protecting privacy.

¹⁰ An example of an AVI system with SAW technology is Norwegian-based Micro Design's Queuefree-Tag. Micro Design's passive tag (priced around NOK100 in 1990 [US\$16]) weighs about 31 gm [1.1 oz] and operates at the reserved frequency of 856 MHz.

¹¹ A passive tag (like the one from Amtech or Micro Design) is beam powered and has an almost indefinite service life because it contains no movable mechanical parts. A (semi-)active tag is battery powered and has a service life of about ten years -- which is likely to exceed the life of a vehicle or be overtaken by obsolescence.

broadcasts a radio frequency towards a transponder placed inside the speeding car. The AVI tag 'modulates' the radio frequency which it receives and reflects its encrypted identification code back to the antenna, which is then relayed back to the reader. The reader's function is to interpret the identification code from the signal, decrypt it and validate the code according to predefined criteria. If the security check verifies that a transponder is valid and a motorist's account is fine, an indicator light by the roadside would turn green. A yellow light may indicate that a user's account is low and a red light would indicate that a defective or fraudulent tag is used, at which time the video enforcement system automatically takes a picture of the offending vehicle. (In principle, even though a traffic cop could be dispatched immediately to apprehend violators, in practice they are merely sent tickets in the mail as with speeding violators.) The reader then transmits the data to a central computer system -- composed of a system of commonly used microcomputers and a minicomputer -- which records information such as the identification code, the location, date, time or the vehicle class code and performs off-vehicle charging either by prepayment or postpayment. A motorist can choose to pay in advance or in arrears. For prepayment, a user's account is linked to a bank account and a pre-specified sum is deducted periodically (alongside the toll rate itself) via electronic funds transfer (giro payments) or credit card payment. As is currently done at toll facilities in Europe and the United States, prepayment could also be performed without a bank account by placing a prepaid cash deposit in advance, as with a numbered account arrangement (thus protecting the individual's privacy). For postpayment, conventional monthly or quarterly billing statements can be automatically sent out and straightforwardly processed. Even with automatic *vehicle identification*, the optional nature and wide variety of payment options would therefore not pose a threat to citizen's civil liberties.

Smart card-based systems form the latest state-of-the-art technology in AVI (Thompson, 1990).¹² Smart card technology is based on a two-way communication link between a 'smart' on-board unit and a roadside antenna. An on-board unit is composed of a smart card, a smart card reader and a transponder.¹³ In addition to the standard integrated circuits found in radio frequency tags, the smart transponder possesses a microprocessor which has both read and write capability -- functioning much like a simple miniature computer. Hence, the smart transponder is able to maintain a

¹²As a precursor of the chip card, the plastic magnetic stripe card (as exemplified by the credit card and bank card) is ubiquitous and very cheap to manufacture -- less than a dollar each. The magnetic stripe card suffers from: 1) the defect of being easily copied; 2) low memory capacity; and 3) the requirement for it to be used together with a mechanical, motor driven reader that is unreliable.

¹³The Telepass system is the only smart card system in operation since May 1990 on Italy's Autostrada. In the Italian system, the transponder -- located in the on-board unit itself -- is responsible for transmission and reception of roadside to vehicle information and operates at 5.72 GHz. Hence it is over six times faster than an RF technology which operates at 915 MHz, allowing for added measures of encryption and security. In addition to being a supplier to Telepass, AT&T has recently teamed up with Vapor Canada, Inc. to integrate its 'contactless' smart card used in banking applications (which has the capacity to store four pages of information) with electronic toll collection (Skrzycki, 1991). (A 'contactless' card means that it involves no metal-to-metal contact or movable mechanisms when it is read by an in-vehicle smart card reader.) AT&T's transponder is said to be priced around US\$100 with smart card attachment (Ramirez, 1992). The PAMELA project, developed as part of the Cambridge road pricing scheme, envisions at least two versions of smart card technology: one which contains all the microwave communications circuits in a single credit-card sized unit and another which splits the on-board unit into a small card reader which contains the circuits and a separate smart card which acts only as a value card (Hills and Blythe, 1990). Here we consider the latter, more basic version.

transactions balance independent of a central computer and can perform simple arithmetic operations when activated, acquiring the function of an electronic purse -- similar to a phone card or a stored value card available on metro systems.¹⁴ Whenever a vehicle passes a charging point, the on-board unit can be programmed to emit a bleep or a tone to signal the completion of a valid transaction (Dutch Ministry of Transport and Public Works, 1989). The smart card can be revalued at designated machines located at certain fuel stations after the decrements reach a threshold level, whereupon a warning yellow light emitting diode (LED) on the in-vehicle unit to which the card is attached is automatically turned on. (This is the modern hands-off version of operating a mechanical on-vehicle meter by hand as envisioned in the Smeed Report, so I call its electronic equivalent 'on-vehicle metering'.) Other functions include the capability of monitoring -- with the use of designated machines -- a previous history of the record of the transactions made (up to 200, say), possibly for the purpose of contesting any alleged discrepancies. The prime advantage of smart card-type AVI technology relative to microwave AVI alone technology is that there is no paper trail, and that anonymity/privacy is assured. A second advantage of smart card system is that it obviates the need to maintain a costly central charging system capable of handling all the separate user accounts. The latter feature is a requirement -- and shortcoming -- of one-way AVI systems. A third advantage is that a charge that is deducted instantaneously would presumably have a greater impact by making the driver more keenly aware of a trip's cost (especially via an audio beeper and a LCD visual display of the account balance) -- and thus modifying his travel behavior -- than a billing arrangement settled by credit card at the end of the month. The disadvantages include the fact that the theft of an electronic purse becomes a potential problem precisely because of its nontraceability -- whereas if a radio frequency-based AVI tag is stolen, it becomes worthless once it has been reported lost (as with a credit card). Hence the major strength of the smart card system is also its vulnerable point. This problem could be partially addressed if the maximum denomination of the smart card's account balance is limited and the penalty high. It has also been suggested that a smart card could be keyed in (with a PIN number) by the user to operate in tandem with the owner's in-vehicle unit, but the entire unit would still be a potential target of theft. The other chief disadvantages of smart cards are that they require complex vehicle to roadside communications and that multi-lane problems still need to be overcome entirely, as compared with microwave AVI systems which are less vulnerable to those problems. Sophisticated vehicle to roadside communications could be used as an opportunity to integrate electronic route guidance and information systems with the smart card automatic debiting system. The use of smart cards for AVI, despite their higher cost vis-a-vis microwave AVI, may be integrated with the growing use of smart cards in several banking systems in France and Japan, making them more appealing in the future.

As an intermediate step to a full smart card system, a simpler memory tag which has some read and write capability can be used (see footnote 9). One such system was tested experimentally since November 1987 at a tunnel in Ålesund, Norway. It operates on similar frequency and transmission speeds as the above-mentioned smart card system

¹⁴In computer jargon, a phone card is a chip card without intelligence and is of the read-only memory (ROM) type. On the other hand, a smart card (as used on a large scale in several banking applications in France) is a chip card with both a microprocessor and a memory, of the electrically erasable, programmable and read-only memory (EEPROM) type.

and allows vehicles to travel up to 60 kph [37.5 mph] by the tollgates.¹⁵ However, it does not have as much flexibility as, or the varied uses of, a standard commercial smart card with banking applications. In August 1992, the Illinois State Toll Highway Authority adopted a 'smart' transponder system for its Illinois Tollway.¹⁶ This technology has features of a smart card system such as read-write capability performed at freeway speed. It is equipped with a LCD visual display for checking toll and parking account balances as well as an audio system that is capable of warning drivers that electronic toll collection or accidents are to be expected a mile ahead. This allows ample time for the motorist to avert bottlenecks.

The advantages of electronic toll collection vis-a-vis manual toll collection are many. Vehicles do not have to slow down, form queues and create congestion because of the transactions cost of manual toll collection. Vehicles can travel at the desired speed (well beyond the current speed limits), with instantaneous debiting of accounts being undertaken at reliability and accuracy levels exceeding 99.9%.¹⁷ Nonstop traffic results in smooth traffic flow and high throughput of 1200 to 2000 vehicles per lane-hour -- triple to more than quintuple the throughput of a conventional manual toll lane. Further, no stopping and paying means decreased fuel consumption, lowered risk of accidents, pollution and road deterioration (especially the road damage caused by heavy vehicles' alternate braking, stopping and starting action). Gone are huge toll plazas with large plots of land and in their places are gantries (or nothing, if in-pavement antennas are used). In some AVI systems, the motorist is instantaneously notified by a green light (indicating a valid account), a yellow light (indicating a low account), or a flashing red light (indicating a depleted account or a malfunctioning tag). State-of-the-art technology does not need major road work, as was required for the outdated Hong Kong electronic road pricing technology in 1983-85; it requires, at most, that a small slit be cut on the pavement to embed a thin electronic loop, and that this be covered over with sealant. With in-pavement antennas installed in such a discreet fashion, the road surface appears to have crack seals on it and is unobtrusive compared to gantry-mounted antennas. In short, great strides have been made in AVI technology, which draws us much closer to feasible electronic road pricing in a city-wide context.

2.2.2 Examples of AVI systems

A simple turnkey AVI system began daily operation at the Crescent City Connection Bridge, New Orleans, United States, in January 1989. Since it was a retrofitted AVI

¹⁵Based on microwave technology, this intermediate system is called the Programmable *RE*Mote *ID*entification (PREMID) system. Using a match-box sized, semi-active tag powered by a long-life lithium battery, it operates at 2.45 GHz -- still a relatively fast transmission rate -- and up to a distance of 5 meters [16 ft]. The PREMID tag can handle up to 32 Kbytes of memory. A more advanced PREMID transponder by Sweden's Saab Combitech Traffic Systems with read-write capability was tested beginning Spring 1992 at the Eastern Harbour Tunnel in Hong Kong.

¹⁶In the winning bid, AT/Comm Inc.'s cigarette-pack-sized, microprocessor-based transponder is priced at US\$37 each -- about 35% less expensive than competing smart card transponders. This read-write tag (containing 16,000 bytes of data) has the twin advantage that it avoids the need to maintain a costly central computer system required of one-way AVI systems and is capable of fully protecting motorists' privacy while they are traveling at expressway speeds. The AT/Comm tag can store up to 24 separate accounts, potentially overcoming the problem of different toll authorities and jurisdictions sharing the proceeds of the same account.

¹⁷Figures are based on tag-based AVI systems as reported in company brochures (from Amtech System Corporation and Micro Design; see following footnote).

system on existing tollbooths, the system was installed for slightly less than a million US dollars. The operating cost is merely a maintenance contract with the AVI supplier -- Amtech -- and four sales clerks and a fraction of a technician's time, which comes to over US\$100,000 a year. With about 30% AVI users for an average daily traffic count of 60,000, the cost per (AVI) transaction comes to less than 4US cents at 1990 prices. Due to low capital cost of US\$1 million, the cost per dollar of toll financing is only around 1%.¹⁸

The second set of figures presented here is based on the information proposed in 1990 for the Dulles Toll Road, Virginia, which connects the Dulles Airport to Washington, D.C. Their much delayed so-called Fastoll system is a fully integrated toll and AVI system, which includes enforcement cameras, fiber optics, communications, barriers, variable message signs and conventional toll equipment, etc. This accounts for the fact that the system is estimated to average US\$16.5 million in capital cost and US\$5 million in operating cost in 1990.¹⁹

With an average daily traffic count of over 70,000 and the total number of transactions of 250,000 (due to a car passing multiple toll points), the cost per transaction comes to an average of US7.7 cents in 1990. Because of the relatively high capital cost of the system (including conventional toll equipment), the revenue-cost ratio is only about 1.6. Even so, the advantages of having such a sophisticated system of electronic toll collection is the indirect savings of not building, equipping and staffing approximately 100 additional toll lanes. After all, highway construction cost is in the range of US\$1.25 million per kilometer in 1990. (An attended (manual) toll lane costs US\$176,000 a year - 11 times more costly than an AVI ('Pikepass') lane of US\$15,800 a year, reports the Oklahoma Turnpike Authority.) Dedicated telecommunications links, although not required, were chosen to improve security. As of this writing, the system has gone through two rounds of bid proposals and should be in operation soon.

In the two case studies, one actual and the other proposed, the issue of privacy is not important because travelers can voluntarily participate in electronic or manual toll collection. The issue of road work is also not crucial because a minimum of it is needed. Besides Crescent City Connection and the Dulles Toll Road, AVI toll collection is increasingly popular in a number of places:

- The world's first electronic toll collection took place in October 1987 in Ålesund, Norway. Though the traffic was modest with only 3,000 vehicles a day, 60% of the daily users were electronic tag holders (Waersted, 1992). In October 1988, electronic toll collection also started on a freeway in the eastern part of Trondheim.
- The 27-kilometer long Dallas North Tollway in Texas has a fully implemented and retrofitted AVI system of 60 lanes for toll tag users since August 1989. This system was installed by Amtech Corporation for free, hence users are charged US\$2 a month

¹⁸ Usage of the then current Amtech technology by the toll authority of the Louisiana Department of Transportation and Development indicates a "99.9% reliability" level (thus appearing to verify manufacturers' claims) and a very cost-efficient operation (since use of AVI reduces personnel costs three times). A drawback of the system in use in 1989-90 is that enforcement was carried out (without an add-on video recording system) by requiring that all vehicles slow down (and perhaps come to a stop) at the tollbooth until the electronic security system verifies the validity of the transponders before lifting the automatic barriers. This is done despite the fact that the technology is fully capable of handling speeds well beyond the speed limit. Motorists in New Orleans place a US\$25 deposit for the use of an Amtech TollTag®.

¹⁹ The Virginia Department of Transportation opted for an out-of-sight transponder to be externally mounted underneath the vehicle and scanned by in-ground antennae (see DeLozier, 1990).

for rental of the transponder and a premium of US\$ cents per transaction for using the nonstop technology (Roth, 1991).

- An example of smart card technology applied to a 'closed' toll road network has been implemented by Autostrade S.p.A. in Italy's autostrada connecting Milan, Florence, Rome and Naples. In operation since April 1990, the technology assures the privacy of its users by debiting the smart card at the appropriate toll rate when vehicles are driven past two charging points -- an entry and an exit point.²⁰
- On the ACESA highway in Barcelona, Spain, electronic toll collection started in April 1990 by the Autopistas Toll Authorities. A more full-fledged system operating on three highways is expected before the end of 1992.
- The Port Authority of New York and New Jersey switched over from a surface acoustic wave technology to microwave technology for buses as early as April 1988 using the Lincoln Tunnel. In Fall 1990, the Authority also began operation for passenger cars on the Goethals Bridge using a fully compatible system.
- The Esterel-Cote d'Azur Toll Agency, which operates the 250 kilometer long ESCOTA highway at Antibes, France also began operation with AVI in November 1990.
- The world's longest double-span bridge of 42 kilometers -- New Orleans' Lake Pontchartrain Causeway -- began operation in December, 1990, using the same (compatible) TollTag system as Crescent City Connection's.
- In January, 1991, the Oklahoma Turnpike Authority began operating the largest electronic toll collection system by installing it on 88 lanes. Charges for toll tag users are registered at freeway speeds whereas non-toll tag users are required to exit the freeway to pay cash manually in order to avert any congestion and traffic back-up as a result of the toll transaction mechanism itself.
- Owned by a private company with the same name, Cofiroute -- a 730 kilometer [454 miles] highway in southwestern France -- has AVI equipment installed at two toll plazas near Tours, France, in May 1991.
- On September 22, 1992, the Harris County Toll Road Authority in Houston, Texas, started electronic toll collection on the 21-mile Hardy Toll Road and the 28-mile Sam Houston Tollway. Motorists who prefer to drive without stopping need only to set up an escrow account with the road authority for a rental fee of US\$1 a month for the use of an EZ Tag.
- An AVI system for special and commercial vehicles spanning Mexico from Tijuana to the border of Guatemala is expected to be installed by November 1992.
- An AVI license plate tag system is scheduled for 18 lanes of the Georgia Route 400 extension in Atlanta, Georgia by March 1993. Four of the lanes will be AVI express-type dedicated lanes, with a lane capacity of at least 1260 vehicles an hour (Spock, 1990). Under optimal conditions, they are capable of achieving the maximum freeway throughput of 1800 vehicles per lane-hour.
- In January 1992, various toll authorities in New York, New Jersey and Pennsylvania (known as the Interagency Electronic Toll and Traffic Management (ETTM) Group) issued a call for proposals for a standardized electronic toll transponder and reader system for the tri-state region, to be tested in 1993 and to be fully operational by 1995

²⁰The Telepass smart card technology is fully applicable to both 'open' barrier-type and 'closed' motorway network. With the latter system, the toll rate is simply calculated by the distance (or time) between two pricing points.

(*Inside IVHS*, February 3, 1992). The prospect of driving nonstop from Philadelphia to New York City looms even larger. The consortium of toll agencies expressed a preference for read-write technology based on two-way communication even though a read-only technology based on one-way communication is considered acceptable. The New York Thruway is the first among the interagency group to implement an electronic toll collection system named E-ZPass, to be operational in 1994-96 (*Inside IVHS*, May 26, 1992).

2.3 Combination of manual and electronic toll collection

2.3.1 The Oslo and Trondheim Toll Rings

The emerging popularity of AVI on toll roads and the success of the technology must have had an impact on proposals for electronic road use charging in Scandinavia. In particular, Oslo Toll Ring began using electronic toll collection with AVI technology in December 1990, following a period of manual toll collection beginning in February 1990. The toll ring surrounding the city imposes an admissions charge for motorists entering it round the clock at any time of the year. Having had the electronic technology in place, Oslo then debated at length the merits of switching from a flat toll to a time-differentiated charging scheme. Trondheim – Norway's third largest city -- has begun in October 1991 electronic road use charging by daylight period to motorists who drive into the city. The operation of both the Oslo and Trondheim Toll Rings is the same as the practice of AVI on toll roads described above. Postpayment via conventional monthly billing statement and prepayment via electronic funds transfer are possible. Unlike most AVI systems on toll roads, the capital costs of Oslo and Trondheim Toll Rings include the construction of toll plazas for the installation of manual toll booths, automatic coin machines, and electronic toll collection. As a result of the plaza environment and a full video enforcement system for reserved lanes, the capital costs are relatively high. With an average daily traffic count of 210,000 and 50,000 during the hours of operation for Oslo and Trondheim Toll Rings respectively, the costs per transaction are *NOK*1.33 [*US*21.2 cents] and *NOK*1.17 [*US*18.7 cents] in 1990 prices respectively, which are much higher than simple AVI systems and twice as costly as manual systems.²¹

All three Norwegian toll rings -- Bergen, Oslo and Trondheim -- are primarily implemented for road financing. In particular, the Oslo Toll Ring was formed for the purpose of financing both roads and public transport in Oslo, with four fifths earmarked for the construction of roads and a fifth for busways. Similarly, the revenues of the Trondheim Toll Ring are used to finance infrastructure which promote public transport, cycling and walking (Tretvik, 1992).

The charging period for the Trondheim Toll Ring is Monday through Friday, 6 a.m. to 5 p.m. (except holidays), which is essentially pricing by daylight hours. The toll rate for (light) vehicles weighing under 3500 kg. [7716 lbs.] is *NOK*10 [*US*\$1.60] per inbound trip if it is collected manually and the rate for (heavy) vehicles weighing over 3500 kg. [7716 lbs.] is twice that of light vehicles. (Motorcycles are not charged at any time of the day and cars are not charged in the evening and at night.) Trondheim Toll Ring is unique

²¹This result appears to be consistent with the findings of Hensher (1991), who concludes that the cost of installation *per lane* for full electronic toll collection in Norway is a third to a half of the cost of a manual toll collection system.

because most (90%) of the users during the peak period (of 6 a.m. - 10 a.m.) and many (85%) of the users during the secondary peak period (of 10 a.m. - 5 p.m.) are electronic tag holders -- a fact that could be due to the free leasing of tags. Electronic transponder users opting for a prepayment (or a postpayment) option are entitled to a discount of 20% off (during the peak period) and 40% off (during the secondary peak period) of the manual toll collection rate of *NOK*10 per inbound entry during daylight hours, resulting in the toll rates of *NOK*8 and *NOK*6 respectively (Tretvik, 1992). (Further discounts are given to those who set up an account -- whether numbered or not -- with a deposit greater than *NOK*500 or even *NOK*2500 a month.) Ten of the 12 cordon entry points are not manned and the large fraction of AVI subscribers make the cost per transaction of the Trondheim Toll Ring comparable to that of the Oslo Toll Ring. A unique feature of the system is that a call box is available on all 12 entry points if a motorist encounters problems with the automatic coin machines, the use of magnetic strip credit cards, or the printing of delayed charges. As in the Oslo Toll Ring, enforcement is carried out by taking videographs of all vehicles passing through and issuing a penalty by mail of *NOK*250 [*US*\$16.89] for the violator. It appears the marked use of differential pricing for the heavy (electronic) users would have some effect of changing the driving behavior of motorists whose trips are not as valuable -- despite the fact that the charging period is nominally by daylight hours only.

Norway has had much experience with financing roads from tolls, as exemplified by the early implementation of the manually operated Bergen Toll Ring in January 1986. Residents in the Oslo and Trondheim vicinity were promised that the rate of constructing the planned road system could be achieved at twice the speed with toll financing. Even though the goal was not traffic restraint, the Oslo and Trondheim Toll Rings had the side effect of dampening travel demand somewhat. Despite the fact that the per trip toll rate for entering Oslo is *NOK*10 [*US*\$1.60] -- twice the rate for entering Bergen -- the initial estimate of the decrease in traffic is only about 5% -- less than Bergen's (Lauridsen, 1990; Larsen and Ramjerdi, 1990).

One natural question to raise is whether a system of 17 toll stations (which includes the entire construction cost of two toll plazas) is worthwhile or not. According to estimates made by Ramjerdi and Larsen (1991), the annualized cost for the Oslo Toll Ring is estimated to be *NOK*96.6 [*US*\$15.4] million.²² The benefits of the toll scheme were estimated by using a simultaneous logit mode choice and traffic assignment model, under the assumption that trip timing, destination choice and location were fixed. For all practical purposes, motorists heading towards the CBD do not have a feasible alternative route to by-pass the toll. (Thus the first two assumptions which pertain to Oslo's cordon system can be contrasted with the Hong Kong zone-based ERP system, which is designed to influence route choice and the (re)scheduling of trips.) For the Oslo system, trip matrices are separated into four time periods -- the morning peak, the afternoon peak, the interpeak, and the off-peak -- and the choice of mode is between private auto and public transport.

²² By assuming that the capital cost is amortized over 15 years and that the real discount rate is 7% (being the official Norwegian rate for public projects), the annualized capital cost of *NOK*255 million (plus the adjusted start-up cost of *NOK*5 million) comes to *NOK*28.55 million per year (slightly over the reported figure of *NOK*26.6 million in Ramjerdi and Larsen, 1991). Together with the annual operating cost of *NOK*70 million, the total annualized cost of the Oslo Toll Ring is *NOK*98.5 million. The benefit-cost ratios reported below are based on their reported figures, in contrast to the simple assumption of a capital recovery factor of 0.125, which is used as a yardstick of comparison across countries.

The economic benefits of the present Oslo Toll Scheme are based on: a) the savings in vehicle operating cost, and the savings in time cost to those travelers who stay and pay the cordon toll, less the *disbenefits* to those whose trips are not undertaken (hence the terminology ‘net benefits’).²³ The savings in operating cost are based on the savings in fuel consumption due to less engine idling time and stop-and-go traffic. In a situation in which private auto trips are dominant, as in Norway, the savings in travel time of the tolled less the welfare loss in consumer’s surplus to those who are tolled off is shown to be less than the gross revenues of the project. The numerical estimates of the benefits are shown in Table 1, classified by time period, in millions of Norwegian kroner in 1990 figures (Larsen and Ramjerdi, 1990; Ramjerdi and Larsen, 1991; Larsen et al., 1991; and Ramjerdi, 1992, with corrections). The results clearly indicate that a round-the-clock, 365-day flat toll of *NOK*10 [*US*\$1.60] for light vehicles (and *NOK*20 [*US*\$3.20] for heavy vehicles) is non-optimal.²⁴ During the peak period, the 10 kroner toll does not cover the high marginal external congestion cost of *NOK*35.60 [*US*\$5.69] incurred during the peak when a vehicle drives inbound to the CBD. On the other hand, during the interpeak and the off-peak period, the current toll exceeds the marginal external cost of *NOK*3.80 [*US*\$0.61] and *NOK*1.40 [*US*\$0.22] respectively. The first set of results in Table 1 indicates that by imposing a lower than optimal toll during the peak, positive benefits of *NOK*38.3 [*US*\$6.1] million follow net of the welfare losses. Similarly, by imposing a higher than optimal toll during the interpeak and off-peak periods, negative benefits result. Thus the annual benefits for all time periods total *NOK*21.9 [*US*\$3.5] million. (Notice that the vehicle operating cost savings form a minor share of the benefits, in contrast to the Hong Kong ERP Scheme). Since the Oslo Toll Ring is designed for a mixture of manual and electronic toll collection, the lane capacity is about 800 vehicles per hour (see Spock, 1990). The delay caused by stop-and-go manual toll payment of 600,000 vehicle trips a week (assumed to be approximately 15 seconds per vehicle) is taken into account. By assuming a value of time of *NOK*30 [*US*\$4.79] per hour and an average occupancy of 1.3, the aggregate annual delay at the toll plazas is on the order of *NOK*4.5 [*US*\$0.7] million. The estimated additional fuel cost due to stop-and-go traffic comes to *NOK*0.4 [*US*\$0.1] million per year. When combined with the cost of building the toll plazas to accommodate manual tollbooths and electronically controlled toll lanes of *NOK*96.6 [*US*\$15.4] million, the net benefits come to -*NOK*79.6 [-*US*\$12.7] million. (Note that the term ‘net benefits’ defined throughout this paper refers to benefits net of the implementation cost of a charging instrument (see footnote in Table 2).) The benefit-cost ratio, taking into account manual toll payment, is 18% and therefore fails a cost-benefit test. From a financial point of view, with adjusted annual toll revenues of *NOK*600 [*US*\$95.8] million, the revenue-cost ratio is 6.2, suggesting that governments would likely find toll financing a worthy pursuit.

²³The change in user cost formula employed by Ramjerdi and Larsen (1991) is based on Williams (1976).

²⁴Note that approximate usage had to be assumed for seasonal pass holders in 1990 and per trip charges will soon be made. Note also that the travel impact of the present toll was around 8%, 4% and 16% reduction during the peak, the interpeak and the off-peak period respectively, not taking into account the effect of seasonal pass holders (Larsen et al., 1991).

TABLE 1: Benefits, costs and revenues of various cordon toll schemes in Oslo, by time period, per year (in millions of 1990 Norwegian kroner)

(a) Results of the 10 kroner (non-optimal) cordon toll scheme in Oslo (i.e., a 24-hour inbound flat toll of OK10 [US\$1.60]) vis-a-vis the base case of no toll

	Savings in operating cost	Savings in travel time	Welfare loss of surplus	Total benefits
Peak periods	2.4	42.1	-6.3	38.3
Interpeak period	0.2	5.0	-7.0	-1.7
Off-peak period	0.4	5.3	-20.4	-14.7
All periods	3.0	52.4	-33.6	21.9
Annual toll revenues, <i>R</i>		600.0		
Annual benefits, <i>B</i>		21.9		
Stops at manually-operated tollgates		4.9		
Annualized cost of toll collection, <i>C</i>		96.6		
Benefits less system cost, <i>NB</i>		-79.6		
Benefit-cost Ratio, <i>B/C</i>		0.2		
Revenue-cost Ratio, <i>R/C</i>		6.2		

(b) Results of an improved ('optimal') cordon toll scheme (i.e., an inbound peak toll of NOK25 [US\$4]) vis-a-vis the base case of no toll

	Savings in operating cost	Savings in travel time	Welfare loss of surplus	Total benefits
Peak periods	6.0	108.5	-19.4	95.2
Interpeak period	0	0	0	0
Off-peak period	0	0	0	0
All periods	6.0	108.5	-19.4	95.2
Annual toll revenues, <i>R</i>		180.0		
Annual benefits, <i>B</i>		95.2		
Stops at manually-operated tollgates		4.9		
Annualized cost of toll collection, <i>C</i>		70.0		
Benefits less system cost, <i>NB</i>		20.3		
Benefit-cost Ratio, <i>B/C</i>		1.3		
Revenue-cost Ratio, <i>R/C</i>		2.6		

(c) Results of a 'perfect' (link-based) fully electronic road pricing scheme (i.e., a marginal cost toll applied link-by-link vis-a-vis the base case of no toll

	Savings in operating cost	Savings in travel time	Welfare loss of surplus	Total benefits
Peak periods	7.6	162.6	-19.3	150.9
Interpeak period	0	0	0	0
Off-peak period	0	0	0	0
All periods	7.6	162.6	-19.3	150.9
Annual toll revenues, <i>R</i>		152.1		
Annual benefits, <i>B</i>		150.9		
Annualized cost of toll collection, <i>C</i>		>70.0		
Benefits less system cost, <i>NB</i>		<80.9		
Benefit-cost Ratio, <i>B/C</i>		<2.2		
Revenue-cost Ratio, <i>R/C</i>		<2.2		

Sources: Larsen and Ramjerdi, 1990; Ramjerdi and Larsen, 1991; Larsen et al., 1991; Ramjerdi, 1992, with corrections; and discussions with the authors.

TABLE 2: Benefits, costs and revenues of car ownership fiscal restraint measure, area licensing and electronic road pricing schemes, by vehicle class per year compared to 1991 reference (in millions of 1985 Hong Kong dollars)

Option	Car ownership restraint measure	Area licensing scheme	ERP scheme A	ERP scheme B*	ERP scheme C	Optimum option
Average peak-hour charge	-	HK\$7.0	HK\$8.4	HK\$9.8	HK\$9.7	HK\$10.5
Annual benefits, <i>B</i>						
Private cars	-29 (-0.10)	124 (0.37)	202 (0.28)	235 (0.27)	216 (0.24)	279 (0.22)
Taxis	38 (0.13)	30 (0.09)	53 (0.07)	61 (0.07)	68 (0.07)	-21 (-0.2)
Public transport	158 (0.52)	118 (0.35)	299 (0.41)	350 (0.40)	389 (0.42)	607 (0.49)
Goods vehicles	134 (0.45)	66 (0.19)	180 (0.25)	225 (0.26)	246 (0.27)	385 (0.31)
Benefits for all vehicles	301	338	734	871	919	1250
As a share of the benefits of the theoretical optimum	[0.24]	[0.27]	[0.59]	[0.70]	[0.74]	[1.00]
Gross revenue generated, <i>R</i>	1200	188	395	465	540	976
Annualized capital and operating costs of charging mechanisms, <i>C</i>	0	10 - 15	49.8	49.0	51.7	>51.7
Benefits less system cost, <i>NB</i> ≡ <i>B-C</i>	301	323-328	684	821	869	1200
Benefit-cost ratio, <i>B/C</i>	∞	22.5-33.8	14.7	17.8	17.8	<24.1
Revenue-cost ratio, <i>R/C</i>	∞	12.5-18.8	7.9	9.5	10.4	<18.9

Notes:

HK\$7.8 = US\$1 and HK\$10.1 = £1 (1985 figures).

CPI (1990)/CPI(1985) = 1.48 (Conversion factor using the Consumer Price Index for all items)

Figures in round parentheses are market shares.

* ERP Scheme B is actually the Area Pricing proposal (with slight variation) simulated in Transport Department and Wilbur Smith and Associates (1989).

Given that ERP Schemes A, B and C increase in complexity and zone-to-zone charge levels, the simulated peak-hour charges are by-products of the simulations. Benefits include the savings in travel time and operating cost of the tolled and the disbenefits of the tolled off, hence the term 'net benefits' was used in the following sources, when referring to these benefit figures. The net benefit figure used here nets out the cost of toll collection.

Sources: Constructed from Transpotech (1985), Tables 8.5 and 8.6; and Harrison (1986), Tables 2 and 3 and text. Unpublished figures of the peak-hour charges are by courtesy of Bil Harrison.

Given that the electronics are already in place, a question that arises naturally is whether a large fraction of the benefits from road pricing could be reaped by imposing a crude cordon toll during the peak period only. For several years, it has been argued in Norway that a toll of about *NOK*20-25 [*US*\$3.2-\$4] would reduce traffic volume by about 20%. It was found that an inbound toll rate to Oslo of about *NOK*25 [*US*\$4] would approximate marginal external cost (Larsen and Ramjerdi, 1990).²⁵ Further, the cordon boundary needs to be tightened in order to allow through traffic (a significant number of vehicles) to make detours and exercise route choice. Thus, by imposing a marginal congestion toll of *NOK*25 [*US*\$4] (or more precisely, the marginal congestion cost of *NOK*29.5 [*US*\$4.71]) on average during the peak that is somewhat optimal, the annual

²⁵ It is assumed that the cost of environmental pollution and road damage cost are covered by the high gasoline tax, so the marginal external cost during the off-peak period is nil (Larsen et al., 1991).

benefits come to *NOK*95.2 [*US*\$15.2] million. Notice that there are no benefits outside of the peak period since the marginal congestion cost of traffic in these other periods is close to zero. The higher benefits from imposing an improved ‘optimal’ cordon toll during the peak yields numerical benefits which are of the same order as the cost of operating the 10 kroner toll scheme. However, with the inbound peak period only toll, just two short shifts of personnel are needed as opposed to personnel for 24 hours a day. Hence the reported figure for the cost of toll collection is a lower amount of *NOK*70.0 [*US*\$11.20] million a year. The benefits, net of the cost of implementation, come to *NOK*20.3 [*US*\$3.2] million, with the benefit-cost ratio being 1.3 vis-a-vis a base case policy of doing nothing. Interestingly, the ‘optimal’ toll revenues are less than a third of the revenues derived from the ‘non-optimal’ toll scheme in Oslo, but the revenue-cost ratio is 2.6. Notice that the cordon scheme differs from the idea of tidal flow charging, which is in accordance with the direction of peak period demand (as in Hong Kong’s ERP Scheme B). This means that a round trip which incurs a marginal congestion cost of *NOK*25 [*US*\$4] in each direction -- one way during the morning peak and the other way during the afternoon peak -- is charged once, i.e., half the externality costs, unless it is a through trip across town. The benefit-cost ratio has increased more than six times whereas the revenue-cost ratio has decreased by 60%, suggesting that a social welfare maximizing toll may not necessarily be a revenue enhancing one. While an ‘optimal’ toll is two and a half times more than the ‘non-optimal’ toll, it yields two-thirds less revenues to the government. If the current practice of earmarking toll revenues is continued, then it would seem ‘fair’ that those who cause congestion are the ones who should pay for them, while simultaneously enjoying the fruits of improved transport infrastructure.

If a motorist were to be charged for the marginal external cost he or she imposes on each link that is traversed in a given trip, the benefits from doing so would come close to a ‘perfect’ road pricing scheme. Thus the benefits of road pricing increased by six-tenths from *NOK*95.2 [*US*\$15.2] for the ‘optimal’ cordon scheme to *NOK*150.9 [*US*\$24.1] million for a ‘perfect’ road pricing scheme. The fact that, with ‘perfect’ road pricing the welfare loss for those who have not undertaken the trip is higher and the revenues lower suggests that travel demand is relatively elastic. The large benefits come about because of the avoided trips which would have caused high marginal external costs. As a result, the net benefits of the system increased further fourfold to *NOK*80.9 [*US*\$12.9] million and the benefit-cost ratio increased to 2.2. The costs of installing the electronic toll collection system route by route will clearly not be cheap. Hence the benefit-cost ratio will be less than 2.2. From a financial viewpoint, with ‘perfect’ road pricing, the revenues dropped from *NOK*180 [*US*\$28.8] to *NOK*152.1 [*US*\$24.3] million, and the revenue-cost ratio decreased to 2.2. Thus, the fear of government collecting high toll revenues as one moves to a ‘perfect’ road pricing scheme does not seem to be borne out by these simulations. Estimated benefits are just below estimated revenues, suggesting that a benefit-maximizing pricing scheme is on average ‘fairer’ than it is generally perceived.

The Norwegian experience appears to demonstrate that toll financing and welfare maximizing objectives may not be correlated since they may go in opposite directions. That is, a (low) flat rate, 24 hour toll may maximize revenue but not net benefit. Per contra, a differential pricing strategy would enhance social welfare but not raise as much revenue. Data from Oslo has demonstrated that a ‘perfect’ road pricing scheme yields significantly higher benefits vis-a-vis a crude ‘optimal’ cordon scheme. By merely imposing a simple peak period toll, however, a nontrivial proportion of the benefits of a

'perfect' road pricing scheme and several times the benefits of the flat toll scheme could be reaped too. Further, the cost of toll collection of such a crude 'optimal' scheme appears to be manageable for the size of a city such as Oslo. The simulation results from Norway also show that toll financing would require a lower toll whereas a welfare enhancing pricing strategy would suggest a higher toll. Still, a benefit-maximizing pricing strategy yields a benefit-cost ratio that happens to be the same as its revenue-cost ratio. Perhaps local authorities should only approve toll financing projects which pass the benefit-cost test.

The simulation results, which show that road pricing is 'fairer' than formerly perceived, have contributed to informed debate about the possible introduction of road pricing in Oslo.²⁶

2.3.2 Road pricing on a cordon basis in Stockholm and Gothenburg

The application of AVI technology for electronic road pricing on a cordon basis in order to reduce congestion and environmental degradation was proposed for the Stockholm and Gothenburg regions in 1989. Since an electronic road pricing system is a fully-fledged AVI system extended to an entire area or city, with charging done on a point pricing basis each time a vehicle passes by an electronic reader, the costs would be higher than a simple AVI system for toll roads. In particular, the capital and operating costs hinge on the number of pricing points and transponder tags and the complexity or sophistication of the system. The Swedish proposals for the Stockholm and the Gothenburg regions are based on the principle of marginal social cost pricing, including the pricing of environmental pollution, and the agreement to channel the revenue proceeds to public transport and road construction. Three major political parties reached a final agreement in September 1992 to use a combination of manual and electronic toll collection system -- as in the Oslo Toll Ring -- to finance transport infrastructure for the Stockholm Region, with the possibility of introducing differential pricing (see Appendix 2).

On January 3, 2006, Stockholm began a 7-month congestion charging pilot scheme aimed at reducing traffic congestion and improving air quality. Motorists entering or exiting the toll ring encircling the inner city of Stockholm are charged by time of day. Charging hours are from 6:30 a.m. to 6:29 p.m. on a regular weekday, with charges per passage ranging from *SEK*10 (*US*\$1.25) to *SEK*20 (*US*\$2.50).

2.3.3 The Hong Kong electronic road pricing and area licensing schemes

An earlier, full-fledged road pricing system on a multiple zonal basis was conducted in Hong Kong in 1983-85. Tested within a congested, multi-lane environment, the field trials based on a sample of 2500 vehicles proved that the Hong Kong Electronic Road Pricing System (ERP) was a technological success. Unlike the simple cordon-based electronic road pricing schemes proposed in Sweden, the system operates on five different time periods through a 12-hour day from 7 a.m. till 7 p.m.): the morning peak, the afternoon peak, the shoulder peaks, and the interpeak. Shoulder peak charging, immediately before and after the morning and afternoon peaks, was designed to deal with the boundary problems of Singapore's ALS by smoothening out the traffic.

²⁶ As of January 1992, the toll for entering the CBD increased by one krone (from *NOK*10 to *NOK*11).

Shoulder peak charges are half the peak charges, whereas the off-peak period from dusk till dawn is not charged. Under the ERP proposal, all private cars in Hong Kong are required to be fitted with a nonremovable, videocassette-sized ‘electronic number plate’ (weighing less than a kilogram) mounted underneath the vehicle.²⁷ Some road work was required for the 18 toll sites established for the pilot stage, involving reconstruction of the road surface, installation of electronic loops, and ducts for power and telecommunications cables underneath the road. (The direct (passive) charging technology available now is portable, pocketable and transferable, and does not require major road work.)

ERP has three pricing schemes. Scheme A is the simplest in design, and lowest in the level of charges, the number of zones and geographical coverage; Scheme B introduces tidal charging that matches the direction of peak demand; and Scheme C captures short trips as well as being the most complex in design and highest in the level of charges, the number of zones and geographical coverage. Imposing an optimal congestion toll of HK\$10 [US\$1.28] in 1985, achieves the theoretical maximal benefit level in the form of savings in travel time and vehicle operating costs, less reduced benefits for those travelers who are tolled off the road (see section on ‘The Effects on the Tolled, the Tolled off and the Untolled’ in Hau (2005a)).²⁸ This annual benefit figure amounts to HK\$1,250 million [US\$160 million] in 1985. The simulation results, with their distributional impacts by mode for the reference year of 1991, indicate that Schemes A, B and C achieve respectively six tenths, seven tenths and three quarters of the maximal benefits associated with the theoretical optimum option of HK\$1,850 million [US\$237 million] in 1990 equivalent (see Table 2).

Since electronic number plate (ENPs) (together with an additional 10% cost for installation) were priced at HK\$460 [US\$59] each in 1985, the cost of the 210,000 ENPs make up about half of the system capital cost of HK\$240 million [US\$31 million].²⁹ Under the one-horse shay assumption of a capital recovery factor of 0.125, the annualized capital cost is then HK\$30 million [US\$3.85 million] and the annual operating cost is HK\$19.80 [US\$2.54 million], representing three fifths and two fifths of the total annual cost respectively. The annual benefit-cost ratios are 14.7, 17.8, 17.8 and 24.1 for each of the three scenarios and the theoretical upper bound option.³⁰ With traffic growth and technological improvements, the benefit-cost ratios will most likely rise. The number of trips made by private cars is forecast to be 549,450 per week day in 1991 and the annualized capital and operating costs amount to just under HK\$50 million [US\$6.38

²⁷ The now out-dated technology was first developed in the early 1970s by the U.K. Transport Research and Road Laboratory and used on the British Rail High Speed Train signaling system and the Glasgow Underground train control system (Transpotech, 1985, pp. 3.5).

²⁸ The economic benefits from ERP are based on: 1) vehicle owners’ savings in operating costs; 2) passengers’ savings in travel time; and 3) public transport riders’ savings (in time); less the welfare loss to those who are tolled off (i.e., the *dis*benefits from generated traffic). Hence Transpotech (1985) and Hau (1989, 1990) call these annual *net* benefits instead. In this paper, net benefits refer to benefits net of system cost.

²⁹ Since then, the price of a passive transponder has fallen by about two thirds and continues to fall.

³⁰ The slight difference in annualized costs for ERP Schemes A, B and C, reflect the fact that the capital cost varies somewhat in relation to the 130, 115 and 185 toll sites required respectively for each scheme.

million] in 1985.³¹ Using the number of operating days per year of 260, the system cost per transaction is HK\$34.9 cents in 1985 [US\$6.6 cents in 1990]. Even though over 10% of the capital cost and about 12-1/2% of the operating cost are required for the 'data capture' enforcement system, the cost per transaction would be even lower if account were taken of multiple transactions, that is, crossing several screenlines a day.³²

In comparison with other mechanisms, electronic road pricing fares well. The annual benefits of a car ownership fiscal restraint measure -- an indirect charging method levied on vehicle ownership via annual license fee discussed earlier -- amount to HK\$301 million [US\$38.6 million] in 1985, about a quarter of those of the optimum option and less than half of those of ERP Scheme A (see Hau, 1989, 1990).³³

A Singapore-type area licensing scheme was actually tested and formally evaluated for Hong Kong in 1985.³⁴ A typical supplementary fee of HK\$7 each [US\$0.90] for vehicles crossing a screenline (in either direction) which encircles the central business districts tallies to about HK\$20 [US\$2.56] each day in ALS fees. The annual benefits of area licensing amount to HK\$338.4 million in 1985 [US\$64.2 million in 1990 figures].³⁵ This benefit figure from supplementary licensing makes up slightly more than a quarter (27%) of the benefits of the theoretical optimum option and less than half (46%) of those of ERP Scheme A. Despite the fact that these dollar benefits are slightly more than those of the car ownership fiscal restraint measure, the latter policy is a sledgehammer approach; it achieves a city-wide reduction in congestion by drastically *lowering* the level of car ownership (for four years) as well as eliminating economically worthwhile trips altogether. Further, the car ownership restraint measure is widely (and correctly) perceived to be inequitable by limiting household car ownership to the wealthiest, the top decile of the population (Hau, 1988).

The annualized cost of supplementary licensing as in Singapore is estimated to be in the range of HK\$10 - \$15 million in 1985 (or US\$1.90 - \$2.84 million in 1990 figures). The annual benefit-cost ratio for two separate zones (one on Hong Kong Island and the other in Kowloon) under an area licensing scheme is 22.5 to 33.8, even surpassing the benefit-cost ratio of 25 for the theoretical optimum of ERP -- the upper bound reference

³¹ The average number of transactions per weekday was estimated by taking the proportion of those who 'stay and pay' (45%) and the total number of peak users (374,000) and interpeak users (847,000) remaining under Scheme A (Transpotech, 1985, pp. 2.69 - 2.70). (Relative to Scheme A, Schemes B and C have less transactions due to the higher charges, so the costs per transactions would climb by 12% and 22% respectively.) The cost per transaction would be lower if one computes all the results on a six-day work week basis rather than five.

³² If one were to use the number of vehicles forecast for 1991 of 275,000 (as opposed to using the 210,000 ENP figure on which the capital costs are based), the number of trips averaged per weekday by a motorist is exactly 2.00. This fortuitous result would make the Hong Kong figures comparable with manual charging and Singapore's ALS, etc., since the charges made elsewhere could be viewed as a round trip charge.

³³ The figure includes the disbenefits of those restrained or would-be car owners who are 'taxed off' from being able to own a private car (because of already existing hefty first registration taxes and annual license fees). The disbenefits amount to a total of HK\$244 million [US\$31 million] in 1985 (Harrison, 1986, Table 3).

³⁴ Note that the set of models used by Harrison (1986) and Harrison et al. (1986) allows for changes in mode choice, trip timing and destination, but not route choice. Most of the effects of the options tested are due to mode choice (90%), some of it to trip time change (10%) and a very minor part is due to destination change. Hence the flexibility of the models used in the exhaustive Hong Kong study on road pricing does allow for rescheduling, which overcomes one of Wilson's 1990 criticisms of the Singapore ALS.

³⁵ Taxis are charged at HK\$4 per trip [US\$0.51] under supplementary licensing but are exempt under ERP schemes A, B and C.

level of the benefits achievable under direct road pricing.³⁶ Suppose the benefits of time savings are ignored and sensitivity analysis is performed, the annual benefits for the car ownership restraint measure, area licensing scheme and ERP Scheme A amount to HK\$18.8 million [US\$2.41 million], HK\$56.3 million [US\$7.22 million], and HK\$281.5 million [US\$36.09 million] respectively. Note that the monetary benefits alone make up 6%, 17% and 38%, respectively, of the total economic benefits. In other words, the monetary benefit-cost ratio for area licensing ranges from 3.8 to 5.6, and for ERP Scheme A the benefit-cost ratio is 5.7 coincidentally.

The cost per transaction is conservatively estimated to be HK7.0 to 10.5 cents per transaction [US1.3 to 2.0 cents] in 1985, making area licensing the least costly scheme vis-a-vis ERP. Because of its very low cost -- both capital and recurrent -- the revenue-cost ratios bracket the range of 12.5 and 18.8. However, it turns out that a single cordon could not be found to neatly encompass the congested areas of Central District in Hong Kong (but could be for Tsim Sha Tsui in Kowloon). Thus, this potentially attractive area licensing scheme faced practical difficulties of implementation and ranked less favorably relative to ERP. Further, other factors including: the single coarse level of charge, the long duration (12 hours) of a unitary charging period, the preponderance of overnight parkers being garaged within the zone, and the small level of benefits obtainable under supplementary licensing vis-a-vis the ERP Schemes, all contribute to ALS being rejected in Hong Kong.

From the municipality's point of view, the revenue-cost ratio is perhaps the more appealing figure. With the auto ownership restraint measure, the additional cost that the government incurs when raising first registration taxes or annual license fees is negligible, given that the administrative structure is already established. Thus, raising (car) taxes has an almost infinitely high financial rate of return and rate of return alone would not be an appropriate statistic to compare road pricing measures. Note also that these indirect fiscal restraint measures are crude instruments with which to tackle congestion. Area licensing schemes' rate of return would be very high because of their low capital cost (this is confirmed by the Singapore evidence) and, provided that the geographical conditions are not insurmountable, these schemes would appeal to local transport authorities facing hard budget constraints. The practical ERP Schemes possess revenue-cost ratios that range from 8 to 10, whereas the theoretical optimum ERP option yields the revenue-cost ratio of 19 -- the highest of all the measures considered.

With the 1989 Green Paper on Transport Policy, the Hong Kong Government again tested public opinion on electronic road pricing under the guise of 'area pricing'. It turns out that the Second Comprehensive Transport Study (CTS-2), which forms the basis of the consultative Green Paper, shows that area pricing is in fact ERP Scheme B resurrected (Transport Department and Wilbur Smith and Associates, 1989, Figure 9.3 and Table 9.5).³⁷ A slightly lower charge (two thirds) of the original 1985 ERP Scheme

³⁶These numbers were adjusted from daily benefit figures (Harrison, 1986, Table 3) to annual figures by 188 days, possibly an underestimate. The factor of 188 was found by dividing the known aggregate annual benefit figure of ERP Scheme A of HK\$734 million [US\$94.1 million] (Transpotech, 1985, Table 8.5) by the daily benefit figure of HK\$3.898 million [US\$0.50 million]. In a discussion with Bill Harrison, it was suggested that the simulation results for the 1991 reference figures were converted to 1985 dollar terms, under the assumption that real income (and hence time savings) increased by 33% during that time period.

³⁷Area pricing is a variant of ERP Scheme B because it extends the charging days to include Saturday (since Hong Kong does operate on a six-day work week). Hence all the above analysis on ERP applies and is quite timely. The reference year is changed from 1991 to 1996.

B proposal was simulated. The CTS-2 concludes that area pricing is technically the best means of combating congestion in selected areas. Dogged by continuing concerns about the potential intrusion of privacy by 'big brother' and accentuated by the issue of 1997 (when Hong Kong will be returned to China), the Hong Kong Government revealed in the ensuing White Paper of 1990 that it has decided to retain area pricing by electronic devices as a long-term option and to monitor the technological developments and their applications elsewhere. In 1992, the Government began testing state-of-the-art automatic vehicle identification technology using the Amtech one-way radio frequency-based and the PREMID stored value, two-way radio communications systems for electronic toll collection at the Aberdeen and Cross Harbour Tunnels. Full commercial operation using AVI technology followed after legislative changes to the tunnel ordinances and by-laws were taken care of. Given Hong Kong's previous experience, the publicly owned but privately operated tunnel companies have offered their clients full protection from invasion of privacy through the establishment of numbered account arrangements. With AVI technology adopted, the initial flat-rate tolls allows for the possibility of introducing differential tolls when the time is ripe -- the key to combating congestion.

2.3.4 Congestion pricing on a new toll road in Orange County, California

Given the political difficulties of implementing road pricing, a concept that gained momentum is the deployment of state-of-the-art technology for implementing congestion pricing on private toll roads. Motorists would not feel coerced -- as with road pricing -- into paying for the use of a road hitherto *not* regarded as free when offered the choice of using a freeway and a feeway. As part of the advent of the privatization of highways in California (provided for in California's Assembly bill 680), the Department of Transportation awarded four franchises in September 1990 to the private sector to construct and run toll roads in Orange County, California (*Inside IVHS*, February 4, 1991). Opened to traffic in December 1995, the US\$88.3 million State Route 91 (also known as the Riverside Freeway) median project had four additional lanes of road capacity built and operated by a private firm, and would be transferred to the state after 35 years -- known as a Build-Operate-and-Transfer (BOT) scheme. With a rate of return regulation of 17% - 20% cap imposed on the company's capital costs, motorists using the heavily congested corridor were initially charged time-varying tolls ranging from US\$0.25 to US\$2.50 when traversing the ten-mile median strip of the Riverside Freeway. The scheme used by this project came to be known as high occupancy toll lanes or HOT lanes. The SR91 project is regarded as the first test of AVI and congestion pricing concepts in the U.S. (*Public Works Financing*, November 1991).

3. ON-VEHICLE METERING

Direct charging can either take place off a vehicle or with an on-vehicle metering system. The modern equivalent of a mechanical on-vehicle meter is an on-board unit consisting of a smart transponder and a smart card reader, the technology of which was described in the previous section. There are two types of pricing schemes, point pricing and continuous pricing by time and distance. Whenever a vehicle passes a pricing point, the vehicle is charged for crossing it, regardless of whether the motorist encounters another charging point. This type of charging is in contrast to the continuous type, which relies on at least one other pricing point to clock in or out with -- so charging is based on distance or travel time.

3.1 *The comprehensive electronic road pricing scheme of the Netherlands based on smart card technology*

In Continental Europe, some progress in road pricing was made by the Netherlands. In 1988, the Dutch Ministry of Transport established a special task force for *Rekening Rijden* -- which literally means travel accounting or road pricing -- to investigate the feasibility of introducing a comprehensive road pricing experiment scheduled to start in 1992, with complete coverage of the Randstad Area by 1995. Having evaluated various state-of-the-art technologies for electronic toll collection, the Dutch Government decided to pursue the use of smart card technology in electronic road pricing for a zonal-based system.³⁸

As with almost all other major metropolitan areas, the growth in travel demand in the Randstad exceeds the growth in road space. In 1990, car usage was forecast to increase by over seven tenths between 1986 and 2010.³⁹ The Randstad area -- an urban (and interurban) agglomeration encompassing the four major cities of Amsterdam, Rotterdam, the Hague and Utrecht, with a total of six million people (over four tenths of the country's population) -- was targeted to be the testing site for comprehensive road pricing. Clearly laid out in the "Programme of Requirements for the Road Pricing Scheme", the objectives of road pricing are to: a) reduce the growth of car use generally, as measured by total vehicle-kilometers traveled, by 14 percentage points (from 72% to 58%), and that of car use during the peak by 30 percentage points (from 72% to 42%), b) reduce waiting time costs by 19%, so that the area would be almost congestion-free by 1996, and c) use part of the revenues for the financing of roads. The scheme's requirements also specify that the revenues raised must be high enough to repay several privately-financed tunnels, and that excess road pricing revenues should be transferred back to the motorist somehow, such as in the form of a reduction in annual vehicle ownership taxes. In addition, the attributes of a 'good' road pricing system (including enhanced efficiency, flexibility, simplicity, transparency, privacy, reliability, security and enforcement, prepayment option, occasional visitor handling, minimal road work, compatibility, and passing both benefit-cost and revenue-cost tests, (see Hau (2006a), Section 2) are almost all laid down in the general requirements of the Dutch scheme and are mostly met with smart card technology. Even the document for the functional design specification for an automatic charging system spells out the performance specifications in some detail (Intercai, 1989). Specification particulars include the need for the system to handle: a) normal traffic flow and speeds (from 0 to 160 kph for a maximum of six undivided lanes; b) normal road capacity of 2000-2400 vehicles per lane-hour; c) a transmission error rate of less than one in a million; d) a transmission speed for the

³⁸To maintain consistency throughout this paper, I define the term 'cordon-based system' as referring to a system of cordons or rings with concentric circles and the term 'zonal-based system' as referring to a system of zones that are not concentric in nature, as with the Hong Kong ERP Scheme. With such a definition, charging is not necessarily imposed on travel within both cordons and zones. By contrast, the Dutch Government calls their system a (multiple-) cordon based system as distinct from a zonal-based one because they would impose charges for travel *within* a zonal-based system (Stoelhorst and Zandbergen, 1990). This distinction is not semantic in that travel within a zone could cause a great deal of congestion, and that the electronics needed would be much broader in coverage and sophistication, adding to enforcement costs. I am indebted to Heero Pol for his comments and for providing me with the quantitative information on the Dutch proposal.

³⁹The 72% growth in car usage is broken down as follows: population growth (20%), growth in car ownership (30%) due to increases in income and employment, growth in female participation in the driving population (10%) and increase in the level of transport service (12%) (Pol, 1992).

communications link exceeding 100 Kbits per second (achievable by microwave technology in the GHz range); and e) a smart card that has sufficient memory capacity to store at least 200 transactions.

The charges were designed to be *Dfl*3 [US\$1.65] per passage during the peak hours of 8:30 - 9:30 a.m. and 4:00 - 6:30 p.m. and *Dfl*0.30 [US\$0.16] during off-peak hours.⁴⁰ The effects of road pricing during peak-hours for the reference year of 2010 are: a) the decrease in total kilometers traveled of 80% (due to suppressed trips, shorter trips and trips undertaken to alternative destinations); b) a rescheduling of trips to off-peak hours of 5%; and c) a change in mode of 15%. The revenues are estimated to be *Dfl*300 [US\$165] million per year. From 1992 to 2010, the time savings amount to *Dfl*10,000 [US\$5,495] million for those who are tolled and the loss of surplus amounts to *Dfl*440 [US\$242] million for those who are tolled off the road (and on to public transport, say). Thus the benefits come to *Dfl*9,560 [US\$5,253] million in present value terms in 1992. With the total system cost of *Dfl*2,200 [US\$1,209] million for the 18-year period, the net benefits are *Dfl*7,360 [US\$4,044] million and the benefit-cost ratio is 4.3. Also estimated are external benefits such as a decrease in road maintenance costs of *Dfl*450 [US\$247] million and environmental benefits valued at *Dfl*400 [US\$220] million. If one were to include these other external costs and benefits (heretofore not included in other schemes such as Oslo Toll Ring), the social benefits come to *Dfl*10,850 [US\$5,962]. External costs were estimated to include an increase in the public transport subsidy of *Dfl*700 [US\$385] million, migration costs of *Dfl*700 [US\$385] and prosperity losses of *Dfl*2,000 [US\$1,099] million. Thus, the social net benefits come to *Dfl*4,810 [US\$2,643] million and the *social* benefit-cost ratio is 3.2.⁴¹

For purposes of comparison with the other charging mechanisms presented here, conversion to annualized figures is necessary. The capital cost for implementing the smart card technology is estimated to be *Dfl*500 million in 1991, which is equivalent to an annualized capital cost of *Dfl*62.5 [US\$33.3] million in 1990 figures.⁴² Since the annual operating costs are estimated to be *Dfl*55 million in 1991, the total annualized costs (including enforcement costs) amount to *Dfl*117.5 million in 1991 [US\$62.68 million in 1990 figures]. With the total number of transactions estimated to be 500 million per year in the full Randstad area, the cost per transaction comes to roughly *Dfl*0.24 in 1991 [US12.5 cents in 1990 figures]. Thus the cost per transaction is on the order of twice the cost of the scheme for Hong Kong, reflecting the higher cost of microelectronics of a two-way smart card system vis-a-vis a one-way tag-based system. The annualized benefits from time savings of those tolled, net of the disbenefits of those tolled off, are about *Dfl*530.6 million per year [or US\$283.0 million in 1990 figures], with an annual benefit-cost ratio of 4.5, which is close enough to our previous benefit-cost ratio of 4.3 calculated using total figures.

⁴⁰ For time-of-day pricing, other schemes such as setting some other periods at half the peak charges were also tried out.

⁴¹ The social *net* benefit-cost ratio is 2.2. In our context, the relevant comparison of benefit-cost ratios requires that the system cost of alternative congestion charging mechanisms be placed in the denominator and all other costs be counted as negative benefits in the numerator. Heero Pol, Dutch Ministry of Transport and Public Works, estimates that the cost per transaction of AVI and smart card technology are approximately the same.

⁴² The capital costs include the estimated cost of 4 to 5 million smart cards. I am grateful to Heero Pol, Chairman, Toll Collection Project, for providing the above figures and for his insightful comments on the charging mechanisms (see Pol, 1992).

As opposed to road pricing, one could attempt to reduce congestion by the unpalatable alternative of constructing roads, at a cost of *Dfl*30 [*US*\$16.5] billion, up till the year 2010 (Ministry of Transport and Public Works, 1989). The revenue-cost ratio of electronic road pricing using smart card technology is estimated to be 2.6, and the toll revenues collected would help alleviate the pressing demands for road construction somewhat. Nevertheless, even though the Dutch Government made a policy decision in 1988 to introduce a comprehensive road pricing scheme for the Netherlands for the period 1992 to 1996, the scheme floundered on political grounds (Catling, 1990). Apparently, the dedication of toll revenues did not sufficiently assuage the car lobby's fear that this might be yet another revenue-raising device on the part of the government. Further, smart card technology requiring two-way radio communications was not considered sophisticated enough in 1990 to warrant a go-ahead for the road pricing scheme.⁴³ Thereafter, the Dutch Government had chosen to reduce the scale of the first phase of the road pricing project by limiting it to electronic toll collection at the tunnels under the Project Toll Ring. On April 27, 1992, the Minister of Transport announced that a system of supplementary licensing would be instituted for motorists using the main road network during the peak period instead.

3.2 Congestion metering in Cambridge, England

In 1993, Brian Oldridge of Cambridgeshire County Council came up with a unique road pricing scheme based on smart card technology. A prototype on-board unit (transponder plus smart card) -- and its miniaturized version -- was developed as part of the Pricing And Monitoring *EL*ectronically of Automobiles (PAMELA) project, which was one of the projects under the European Community's *D*edicated Road and *I*n-*V*ehicle Safety (DRIVE) research programme⁴⁴.

The proposed scheme works as follows. A cordon is placed around the City of Cambridge and beacons are strategically installed at 17 radial roads which fully control the gateway to the city. Whenever an automobile equipped with an on-board unit containing a valid smart card passes a roadside beacon when 'congestion' occurs, a 'congestion unit' of 20 pence [*US*36 cents], say, is debited electronically on the smart card (Oldridge, 1991). Simultaneously, traffic information by lane is also collected by a real-time data-concentrator, which aids in monitoring the congestion situation. However, the key difference between the Cambridge road pricing concept and all other road pricing systems is that the former is based on *ex post* pricing and the latter on *ex ante* pricing. Congestion charging, in this case, is applied literally -- as and when congestion occurs, without any prior notification -- regardless of whether avenues of escape are available at a congested bottleneck. When an equipped automobile enters the city during the peak hours, the in-vehicle unit is triggered on and is turned off only upon exit or whenever the engine is shut off. Thus the Cambridge system is based on continuous pricing rather than on point pricing, which was the basis of the Dutch smart card system

⁴³ One of the specifications sought for a smart card is that it should contain at least 200 transactions, whereas smart cards produced for a large French banking system at the time could only contain 175 transactions, even before considering the transponder component required for identifying objects which are in motion (Intercai, 1989).

⁴⁴ A microwave communications link using a 2.45 GHz transmission frequently was already tested at Newcastle in 1990 (Hills and Blythe, 1990; Blythe and Hills, 1991; Thorpe and Hills, 1991).

and most other AVI systems.⁴⁵ A ‘congestion unit’ is debited on a smart card when one of the following provisional conditions defining ‘congestion’ is met: the threshold of a pre-specified speed (e.g. 6 mph within a third of a mile or 3 minutes for every half kilometer is reached; or more than four stops are undertaken within a third of a mile).⁴⁶ Even though *ex ante* pricing is on an *expected* congestion rather than *actual* congestion basis, it is consistent with the dictum that price signals be made known to the consumer-traveler beforehand, with the objective of transmitting scarcity values to the rational consumer and the aim of impacting modal split. While the smart card component assures privacy, *ex post* congestion-based pricing does not affect or modify travel behavior as effectively as *ex ante* pricing would.⁴⁷

The plan by the Cambridgeshire County Council was to distribute on-board units with the transponder free of charge to regular users, whereas occasional visitors to the city would have to pick up daily passes from automatic machines at the entrances to the city. The revenues raised from congestion charging were earmarked to improve public transport, for instance, by the construction of a light rail transit system. Full scale field trials were originally expected to begin in 1993-94 but ultimately failed to get off the ground. Still, quite a few are convinced that it is only a matter of time before road pricing becomes a reality in Europe.

Indeed, on February 17, 2003, London successfully introduced a congestion toll of £5 sterling [US\$8] for motorists who drive within the congestion charging zone – a designated 14-square mile area [22 square km] of the city centre – from 7:00 a.m. to 6:30 p.m. on a regular weekday. Without barriers, the nonelectronic scheme is enforced by more advanced automatic number plate recognition via a network of 203 closed-circuit television cameras. Preliminary estimates of the London scheme indicate that the capital cost of the scheme was almost £200 million (in 2003 prices), with an annual cost of £130 million against an annual benefit of £180 million (see Transport for London, 2005). A fraction of the annual cost, £20 million, is used to provide additional buses. Despite residents being given a 90% discount and the handicapped being exempted, congestion in the congestion zone fell by 30% during charging hours compared with pre-charging conditions. Emboldened by its success, the Mayor of London Ken Livingstone raised the congestion toll from £5 to £8 on July 4, 2005.

3.3 The Singapore electronic road pricing system

Singapore -- the pioneer in road pricing – took the bold step of upgrading its simple labor-intensive area licensing scheme into a capital-intensive electronic road pricing system effective September 1998. The initial goal was to turn the 26 manually controlled

⁴⁵ A similar device called Timezone, which charges for congestion on a continuous pricing basis, is designed by GEC-Marconi. The trial for testing the electronic equipment is to begin in the London Burrough of Richmond in 1991.

⁴⁶ At the time of this writing, Brian Oldridge informs the author that the City of Cambridge has abandoned the latter charging criterion. Still, it is possible that problems with safety may arise if vehicles reduce their tendency to stop at pedestrian crossings in order to attain an average threshold speed.

⁴⁷ One of the interesting aspects about the original proposal is that whenever the stored value of a smart card expires and a vehicle’s engine is turned off for more than a minute, the engine electronics (or gas supply) is cut off for enforcement purposes! This is done to ensure that users recharge their smart cards at filling stations, for instance. Although this would reduce the cost of enforcement to society, this tactic may possibly pose as an unnecessary hurdle to political implementation.

gantry points of the ALS into electronically controlled ones, with the intention of eventually turning the scheme into a more sophisticated ERP system. After inviting tenders for both an AVI and smart card system, authorities adopted smart card technology as the basis of their electronic road pricing system. In response to the government's first call for tenders, about 30 international companies submitted proposals, with five finalists chosen in 1991. The installation cost, including an electronic enforcement system, in the mid-price range, was S\$80 [US\$44.2] million and a five-year maintenance contract ran about S\$21 [US\$11.6] million.⁴⁸ Assuming a median bid, the cost per transaction is S72.7 cents [US\$40.2 cents], under the assumption that the morning (7:30 - 10:15 a.m.) and afternoon (4:30 - 6:30 p.m.) peak traffic volumes still remain at the level of 69,000 in 1990 (Public Works Department, 1990).⁴⁹ On the other hand, if the 1990 average daily traffic count of 300,000 during the day (6 a.m. - 8 p.m.) is used when electronic road pricing becomes more encompassing, the cost per transaction is S16.7 cents [US\$9.2 cents].⁵⁰ The capital costs include the costs of smart card units for 520,000 automobiles. Vehicles from foreign countries are not exempt from ERP and those who intend to drive into the Restricted Zone during peak hours are expected to obtain temporary tags at commissioning stations for foreign vehicles. Due to the stringent performance specifications set by the Singapore Government, the wide variation in the submitted bids, and apparent failure to agree on the commercial terms of the lucrative market between the negotiating parties, new tenders were sought in March 1992 based on revised specifications for a smart card system.

It was not until September 1, 1998 did Singapore mount a full-fledged Electronic Road Pricing system, converting its manually-operated whole day area licensing scheme (expanded in 1994) to a fully electronic one using smart card technology.

4. RECOMMENDATIONS OF CONGESTION CHARGING MECHANISMS FOR DEVELOPING COUNTRIES

While the principles of road use charging enunciated here are applicable worldwide, the following guidelines are put forth with developing countries in mind:

- On the basis of benefit-cost calculations, the labor-intensive technology of supplementary licensing outranks the capital-intensive technology of electronic road pricing via AVI and is especially suitable for those developing countries that have a pool of unemployed work force and limited gateways. (A fairly reliable guide to the appropriateness of implementing ALS in a particular city is the citizenry's adherence to general traffic regulations.) This charging instrument is definitely worth revisiting, with the proviso that improved alternatives such as public transport and bypass routes be offered (as in the Singapore ALS).

⁴⁸The bids for the installation costs range from a low of S\$41 [US\$22.7] million (by Philips) for a simple AVI system to a high of S\$164 [US\$90.6] million (by the joint venture of United Engineers and Vapor Canada, Inc.) for a sophisticated smart card system, with numerous add-on options. The bid submitted by United Engineers and Vapor Canada, Inc., for a more basic smart card system was S\$98 [US\$54.1] million. The five-year maintenance contracts for each comes to S\$13 [US\$7.2] and S\$14 [US\$7.7] respectively in 1990 figures.

⁴⁹The number of operating days in the year is assumed to be 283, as with ALS. The corresponding costs per transaction for the low and high bids are S39.6 cents [US\$21.9 cents] and S119.3 cents [US\$65.9 cents] respectively.

⁵⁰The corresponding cost per transaction for the low and high bids are S9.1 cents [US\$5.0 cents] and S27.4 cents [US\$15.2 cents] respectively.

- Cordon pricing via standard manual tollbooths and unattended reserved lanes (as in Bergen) -- supplemented by periodic videographs -- may yet prove to be a worthwhile, labor-intensive technology to consider in developing countries.
- The lesson of using electronic toll collection as in the Oslo Toll Ring amply demonstrates that it is the peak/off-peak pricing strategy, rather than the electronics per se, that is benefit enhancing (as opposed to being merely revenue enhancing).
- Electronic road pricing via AVI alone technology is a viable alternative for the newly industrializing economy whose standard of living is rising but whose rapid urbanization and motorization growth rates are a major problem.
- Since Singapore had successfully implemented its Electronic Road Pricing system with smart card technology in 1998, technological breakthroughs will continue to make this technology worthwhile on both economic and financial grounds. Alternatively, the use of two-way microwave read-write transponders that are less costly and yet fully protect privacy can be considered.
- The disposition of the revenues collected from road pricing is crucial to its success -- be the funds raised by electronic means or not -- and should be explicitly laid out to the public. Based on both experience and conceptual grounds, it appears that earmarking of the proceeds from road pricing would serve as an important prerequisite to the actual implementation of (World Bank-mandated) marginal cost pricing in the road sector.

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REFERENCES

- Abbott, J. (1990) Key role for public transport funding boost in Stockholm's road pricing plans. *Urban Transport International*, August/September, pp. 32-34.
- Ardekani, S.A. (1991) Economic evaluation of toll plaza operations. Paper presented at the 70th Annual Meeting of the Transportation Research Board, Washington, D.C., 13-17 January, pp. 1-35.
- Armstrong, J. (1984) Breakthroughs in vehicle identification. *Railway Age*, pp. 40-48.
- Belcher, P. and Catling, I. (1987) Electronic route guidance by AUTOGUIDE: the London demonstration. *Traffic Engineering and Control*, 28, 586-592.
- Bhatt, K. (1974) Road pricing technologies: A survey. Urban Institute Paper No. UI-1212-11, August, pp. 1-45.
- Blythe, P.T. and Hills, P.J. (1991) Pricing and monitoring electronically of automobiles, the DRIVE project PAMELA: 1. The technology. *Traffic Engineering and Control*, 32, 240-245.
- Catling, I. (1987) Automatic vehicle identification. In *Information Technology Applications in Transport*, Peter Bonsall and Michael Bell (eds.), Chapter 3, VNU Science Press BV, Utrecht, The Netherlands, pp. 41-64.
- Catling, I. (1990) System Convergence -- The Potential for an Integrated Road Transport Environment, 17, pp. 285-299.
- Catling, I., Harris, R. and McQueen, B. (1991) A review of European developments in route guidance and navigation systems. In *Applications of Advanced Technologies in Transportation Engineering: Proceedings of the Second International Conference*, Minneapolis, Minnesota, 18-21 August, American Society of Civil Engineers, New York, pp. 358-362.
- City of Stockholm (1989a) Proposal for an electronic fee system for car traffic in the Stockholm inner city area. The Streets and Traffic Administration, Stockholm, draft, pp. 1-10.
- City of Stockholm (1989b) Zone fee proposal using car cards. Street Department, Stockholm, pp. 1-9.
- Davies, P. (1987) Vehicle detection and classification. In *Information Technology Applications in Transport*, Peter Bonsall and Michael Bell (eds.), Chapter 2, VNU Science Press BV, Utrecht, The Netherlands, pp. 11-40.

- Davies, P. (1989) Testing and appraisal of automatic vehicle identification systems. Selected Proceedings of the Fifth World Conference on Transport Research: Transport Policy, Management & Technology Towards 2001, Yokohama, Japan, 10-14 July, Vol. 11, pp. B355-B363.
- De Lozier, E.J., (1990) How and why AVI? Paper presented at the International Bridge, Tunnel and Turnpike Authority International Symposium on AVI Technology for Toll Collection, New York, 17-20 June, pp. 1-8.
- Department of Transport (1988) Autoguide, pilot stage proposals: A consultation document. March, United Kingdom, 38 pages.
- Foote, R.S. (1981) Prospects for non-stop toll collection using automatic vehicle identification. *Transportation Quarterly*, 35, 445-460.
- Harrison, B. (1986) Electronic road pricing in Hong Kong: 3. Estimating and evaluating the effects. *Traffic Engineering and Control*, 27, 13-18.
- Harrison, W.J., Pell, C., Jones, P.M. and Ashton, H. (1986) Some advances in model design developed for the practical assessment of road pricing in Hong Kong. *Transportation Research Part A*, 20, 135-143.
- Hartje, R.L. (1991) Tomorrow's toll road. *Civil Engineering*, February, pp. 60-61.
- Hau, T.D. (1988) Urban transport. In *The Economic System of Hong Kong*, Henry C.Y. Ho and Laurence L.C. Chau (eds.), Asian Research Service, pp. 190-226.
- Hau, T.D. (1989) Road pricing in Hong Kong: A viable proposal. *Built Environment*, 15, 195-214.
- Hau, T.D. (1990) Electronic road pricing: Developments in Hong Kong 1983-89. *Journal of Transport Economics and Policy*, 24, 203-214.
- Hau, T.D. (1992a) Economic Fundamentals of Road Pricing: A Diagrammatic Analysis. World Bank Policy Research Working Paper Series, WPS No. 1070, December, The World Bank, Washington, D.C., pp. 1-96.
- Hau, T.D. (1992b) Congestion Charging Mechanisms for Roads: An Evaluation of Current Practice. World Bank Policy Research Working Paper Series, WPS No. 1071, December, The World Bank, Washington, D.C., pp. 1-99.
- Hau, T.D. (1998) Congestion pricing and road investment. In Kenneth J. Button and Erik T. Verhoef (eds.) *Road Pricing, Traffic Congestion and the Environment: Issues of Efficiency and Social Feasibility*, Chapter 3, Edward Elgar, Cheltenham, U.K. and Northampton, M.A., U.S.A., pp. 39-78.
- Hau, T.D. (2005a) Economic fundamentals of road pricing: a diagrammatic analysis, Part I – Fundamentals. *Transportmetrica*, 1, 81-117.
- Hau, T.D. (2005b) Economic fundamentals of road pricing: a diagrammatic analysis, Part II – Relaxation of assumptions. *Transportmetrica*, 1, 119-149.
- Hau, T.D. (2006a) Congestion charging mechanisms for roads, Part I – Conceptual framework. *Transportmetrica*, 2, 87-116.
- Hensher, D.A. (1991) Electronic toll collection. *Transportation Research Part A*, 25, 9-16.
- Hills, P.J. and Blythe, P. (1990) Road pricing: Solving the technical problems. *Economic Affairs*, 10, 8-10.
- Inside IVHS, Intelligent Vehicle/Highway Systems Update, February 4, 1991; February 3, 1992 and May 26, 1992.
- Intercai BV (1989) Functional Design Specification: Automatic Passage Charging System. Rijkswaterstaat, Projectteam Rekening Rijden, pp. 1-166.

- Jeffrey, D. (1987) Route guidance and in-vehicle information systems. In *Information Technology Applications in Transport*, Peter Bonsall and Michael Bell (eds.), Chapter 14, pp. 319-351.
- Larsen, O.I. (1987) The toll ring in Bergen, Norway. *Transportation Research Record*, 1107, 41-45.
- Larsen, O.I. (1988) The toll ring in Bergen, Norway: The first year of operation. *Traffic Engineering and Control*, 29, 216-222.
- Larsen, O.I. and Ramjerdi, F. (1990) The toll rings in Norway in the perspective of road pricing. Paper presented at the PTRC Conference on Practical Possibilities for a Comprehensive Transport Policy With or Without Road Pricing, London, England, 5 December, pp. 1-19.
- Larsen, O.I., Mathieu, P. and Ramjerdi, F. (1991) Is 'perfect' road pricing cost efficient? Paper presented at Entretiens Jacques Cartier, Colloque La régulation des déplacements urbains par leux prix, Lyon, France, 4-6 December, pp. 1-15.
- Lauridsen, H. (1990) The toll rings in Bergen and Oslo: Evolution and experience. Paper presented at the East Europe Transport Policy Seminar, Paris, France, 18-21 March, pp. 1-17.
- Malmsten, B. (1992) Traffic and environment in the Stockholm region: The Greater Stockholm negotiation ('The Dennis Package'). Stockholm Council Office of Regional Planning and Urban Transportation, Stockholm, Sweden, pp. 1-17.
- Ministry of Transport (1964) Road Pricing: The Economic and Technical Possibilities. Her Majesty's Stationery Office, London, pp. 1-61.
- Ministry of Transport and Communications (1991) Traffic for Growth and a Better Environment. A Summary of Provisions in Government Bill 1990/91: 87 Relating to the Audit of the Ministry of Transport and Communications, pp. 1-29.
- Ministry of Transport and Public Works (1989) Rekening Rijden: Road Pricing in the Netherlands. Projectteam Rekening Rijden, (Dutch) Ministry of Transport and Public Works, Information Services, 14 pages.
- Oldridge, B. (1991) Congestion metering in Cambridge city. Cambridgeshire County Council, Cambridge, paper presented at the PTRC Conference on Practical Possibilities for a Comprehensive Transport Policy With or Without Road Pricing, London, England, 5 December 1990, pp. 1-14.
- Pol, H.D.P. (1992) Specific Design Elements: Toll Roads. Trend 90/92, Toll Collection Project, Ministry of Transport and Public Works, Rijkswaterstaat, The Netherlands, February 3, pp. 1-49 plus appendices.
- Public Works Department (1990) Electronic Road Pricing (ERP) System. Ministry of National Development, Singapore, pp. 1-8.
- Public Works Financing (1991) SR 91 Milestones Met by CRSS. November, pp. 6-8.
- Ramirez, A. (1992) Venture is developing ways to speed traffic. *The New York Times*, April 14, Section D, pp. 5.
- Ramjerdi, F. (1992) Road pricing in urban areas: A means of financing investment in transport infrastructure or of improving resource allocation, the case of Oslo. Paper presented at the 6th World Conference on Transport Research, Lyon, France, 29 June – 3 July, pp. 1-12.
- Ramjerdi, F. and Larsen, O.I. (1991) Road pricing as a means of financing investment in transport infrastructure, the case of Oslo. Paper appeared in *Public/Private Partnerships in Urban Mobility Proceedings*, OECD/CETUR, Paris, France, 3-5 April, pp. 1-17. An updated version was presented at the 71st Annual Meeting of the Transportation Research Board, Washington, D.C., 12-16 January, 1992, pp. 1-12.

- Roth, G. (1991) Private ownership of roads: Problems and opportunities. Paper presented at the 70th Annual Meeting of the Transportation Research Board, Washington, D.C., 13-17 January, pp. 1-26.
- Seila, A.F. and Wilson, P.W. (1991) Deadweight loss in highway toll collection. *Transportation Research Part B*, 25, 127-141.
- Skrzycki, C. (1991) AT&T, Partner Say Toll-Taking is in the Cards: Venture Offers Electronic 'Smart' Payment System. *The Washington Post*, 6 December, pp. B10.
- Söderström, J. (1988) The Bergen toll-ring system: A way of financing urgent road improvements by user fees. *Routes*, No. 265, pp. 81-87.
- Sommerville, F. (1991) Applications of automatic vehicle identification technology. *Transport Reviews*, 11, 173-191.
- Spock, L. (1990) A new wave in transportation. *Portfolio*, A Quarterly Review of Trade and Transportation, 3, 16-24.
- Stoelhorst, H.J. and Zandbergen, A.J. (1990) The development of a road pricing system in the Netherlands. *Traffic Engineering and Control*, 31, 66-71.
- Tegnér, G. (1991) Road pricing in Stockholm -- Some model simulated experiences. Paper appeared in the Public/Private partnerships in Urban Mobility Proceedings, OECD/CETUR, Paris, France, 3-5 April, pp. 1-28.
- The Social Democratic Party, the Moderate Party and the Liberal Party (1992) Agreement on Enhancing the Traffic Infrastructure in the Stockholm Region. 29 September, Stockholm, Sweden, pp. 1-26.
- Thompson, T. (1990) Road use charging -- The current state of technology. *Traffic Engineering and Control*, 31, 526-532.
- Thorpe, N. and Hills, P.J. (1991) Pricing and monitoring electronically of automobiles, the DRIVE project PAMELA: 2. The scope of automated pricing systems. *Traffic Engineering and Control*, 32, 364-370.
- Transport Department and Wilbur Smith and Associates (1989) Hong Kong: Second Comprehensive Transport Study, Hong Kong Government, Government Printer, Hong Kong, May 1989, pp. 1 - 10-27.
- Transport for London (2005) Central London Congestion Charging Scheme: Impacts Monitoring, Third Annual Report, London: Transport for London, April, 2005.
- Transpotech (1985) Electronic Road Pricing Pilot Scheme: Main Report. May, Main Report prepared for the Hong Kong Government, pp. 1.1-4.40.
- Tretvik, T. (1992) The Trondheim toll ring: Applied technology and public opinion. Paper presented at the joint OECD/ECMT/GVF/NFP conference on the Use of Economic Instruments in Urban Travel Management. 19-19 June, Basel, Switzerland.
- Vickrey, W.S. (1960) Statement to the joint committee on Washington metropolitan problems. *Transportation Plan for the National Capital Region, Hearings, Joint Committee on Washington Metropolitan Problems*, 8-14 November 1959, pp. 454-490.
- Waersted, K. (1992) Automatic toll ring no stop electronic payment systems in Norway: Systems layout and full scale experiences. Paper presented at the Sixth IEE International Conference on Road Traffic Monitoring and Control, 28-30 April, London, England.
- Williams, H.C.W.L. (1976) User benefit analysis in travel demand models. *Journal of Regional Science*, 16, 147-166.
- Wustefeld, N.H. (1988) Toll roads. *Transportation Quarterly*, 42, 5-22.

APPENDIX 1. THE MANUALLY-OPERATED BERGEN TOLL RING, 1986-1992

*A1.1 Background information*⁵¹

The Bergen Toll Ring began on January 2, 1986 within a couple of years after the scheme was first proposed. Following Singapore, it is the second city to charge motorists for entering the Central Business District (CBD). The scheme involved the construction of tollgates at six entry points to the CBD of Bergen, Norway's second largest city.⁵² The tollgates are all manually operated, with about half of the lanes for motorists paying by cash or prepaid tickets and the other half reserved for motorists with seasonal passes (i.e., season tickets) placed behind the windscreen. These passes could be purchased on a monthly, six-monthly, and yearly basis, their purpose being to allow traffic to go through the tollgates at expressway speed. The enforcement of offenders is carried out by occasional videotape recording of license plates in these unattended lanes. Since its inception, the toll rates have remained at *NOK5* [*US80* cents in 1990 figures] for light vehicles such as automobiles, with buses and light motorcycles being exempt. (Heavy vehicles are charged exactly twice the rate of light vehicles and the rate for monthly seasonal pass holders are set at 20 times the daily rate (Söderström, 1988).) The hours of operation for entry have been set at Monday through Friday, 6 a.m. - 10 p.m. (except public holidays) -- not quite daylight pricing. Note that the purpose of setting the toll at a low level is to increase revenues earmarked for road financing. (For purposes of charging for congestion, the toll rate should be higher to have a positive impact and should apply for a more selective time period. With its net toll revenue (totalling 25% of funds for a road program), Bergen was able to obtain a matching grant (25%), and when these grants are combined with regular government funds (50%), Bergen was able to pursue a road construction program within half the time horizon previously envisaged for its road construction program. Citing problems of congestion, air and noise pollution and traffic safety, eight tenths of toll revenues are earmarked for road construction and improvement and two tenths for bus lanes, etc. (to improve public transport).

A1.2 Analysis of results

Even though the principal purpose of the toll ring was not traffic restraint, traffic was projected to fall by 3%. Given that the overall traffic growth of 10% was due to economic growth, it was still found that the isolated (i.e., *ceteris paribus*) impact of the toll ring was that traffic declined by 6%-7% in the first year. In surveys conducted by the Institute of Transport Economics, Norwegian Centre for Transport Research (Larsen, 1987, 1988), the effects of the toll ring were found to be as follows: a) change in route choice was negligible since the topography allows almost no detours; b) there was an internal adjustment for households which are seasonal pass holders and have more than one car, resulting in more car trips undertaken since the additional toll is zero; c) it is unclear whether a change in mode choice from car to public transport had taken place; d) through traffic declined by 6-7%; e) car occupancy seems to have increased slightly; and

⁵¹This appendix is based principally on Larsen (1987, 1988). Extensive discussions with him and insights borrowed are gratefully acknowledged.

⁵²Four of the tollgates have two lanes -- one for motorists paying cash and prepaid (coupon book) tickets and another for users of seasonal passes -- and two of the parallel tollgates have four lanes -- two for cash and prepaid tickets and the other two for seasonal passes. Thus, the total number of lanes in the 6 toll plazas is 16.

f) changes in trip timing are observed at the end of the charging period but the effect is not significant.

Even though only a quarter of all vehicle owners in Bergen are holders of seasonal passes, slightly over half (55%) of the CBD-destined trips are undertaken by these holders every day.⁵³ In particular, seven tenths of trips during the morning rush hours are undertaken by these holders. It was found that seasonal pass holders undertake about 1.7 trips per day on average, implying an effective charge of about *NOK*2.90 [*US*46 cents], (a 40% discount or more) as compared to the standard toll rate of *NOK*5 [*US*80 cents]. From a road authority's perspective, the multiple use of seasonal passes may dampen the effectiveness of cordon pricing as a congestion charging instrument.

AI.3 Evaluation

Trade-offs will have to be made either to disallow seasonal users' implicit rebates and charge directly for their entry, via tollgates, potentially exacerbating congestion and increasing operator costs, or to allow the continuation of seasonal passes with their (invaluable) nonstop nature but their zero (marginal) toll effect. *Prima facie*, it appears that the advantages of the use of seasonal passes mitigates the disadvantages of charging for congestion via tollgates. The videotaping of license plates was done on a periodic but random basis, with the number plates checked against the list of seasonal pass holders' license plates. A tolerable level of about 2% violators was found based on a 5% random check of all vehicles passing through. A fairly hefty fine equivalent to twice the monthly fee was imposed on offenders, apparently with the desired effect. The enforcement cost of monitoring motorists who cheat and the follow-up work of issuing traffic tickets are more or less covered by the revenues derived from such pursuits. Thus enforcement costs are all internalized with this approach to charging for congestion.

The capital cost of the system (including the construction of tollgates, consultant fees, equipment and the publicity campaign) is *NOK*12.8 million in 1986 [*US*\$2.58 million in 1990], and the operating cost (including toll operators' salaries, etc.) amounts to *NOK*7.2 million a year [*US*\$1.45 million in 1990]. The gross revenues total *NOK*55 million in 1986 [*US*\$11.10 million in 1990]. As a toll financing mechanism, the collection cost per dollar of net revenue was 19%. Since this partial dead-weight loss was lower than the high social opportunity cost of public funds estimated to be in the 30%-40% range in Norway, toll financing is therefore regarded as a viable alternative to tax financing and enhances the Toll Ring's *raison d'être*. With an average daily traffic count of 62,000 for 260 days of operation in a year, the cost per transaction (including all enforcement costs) comes to *NOK*0.546 in 1986 [*US*11.0 cents in 1990]. When compared with the Singapore ALS, the cost per transaction is only slightly higher but within the same order of magnitude. This is to be expected since half of all lanes were reserved for seasonal pass holders and were left unmanned. If welfare maximization is pursued in lieu of revenue maximization *per se*, then it is desirable to: a) reduce the number of operating hours, from 6 a.m. to 10 p.m. to perhaps daylight hours 6 a.m. to 5 p.m. (as was done in Trondheim in the 1990s) or to the morning and afternoon peak periods only (as in the revised Singapore ALS post-1989 period) in order to impact the modal split of truly congestion-causing traffic; and b) raise entry prices higher to effectuate a reduction in rush hour traffic. The side effects of this twin policy would most likely be an increase in

⁵³Less than one tenth of Bergen's population live inside the toll ring (Söderström, 1988).

revenues, both because of the relatively unresponsive (i.e., inelastic) nature of peak demands as well as the savings in toll operators' salaries. Alas, no benefit-cost studies have been performed on the Bergen Toll Ring to cross-check my intuition.

A1.4 Lessons for implementing cordon pricing via tollgates and reserved lanes

Some lessons to be drawn from the Bergen Toll Ring of charging for congestion are as follows: a) For cities with limited entries (and detours) in developing countries such as Lagos, Bombay and Jakarta, manual charging of congestion via tollgates is potentially feasible. b) If the fraction of regular commuters is high, the use of reserved lanes for holders of seasonal passes can be justified. The use of reserved lanes would both reduce the delays that are the major drawback of cordon pricing via tollgates, and lower the capital and operating costs of the toll facility itself. c) Toll collection is a well-established technology for the construction of toll roads, tunnels and bridges, with almost universal acceptance in terms of administration. d) The use of toll revenues to finance road construction and/or public transport seems to appeal to road users as being 'fair' and appears to be a political prerequisite to implementation.

APPENDIX 2. THE ELECTRONIC AND MANUAL ZONE FEE PROPOSALS OF STOCKHOLM, 1989 AND 1992

A2.1 The electronic and manual zone fee proposals of Stockholm, 1989

In order to combat environmental pollution and congestion, the City of Stockholm proposed that a wholly electronic fee system be imposed on automobiles entering Stockholm (City of Stockholm, 1989a). The inner city is marked by a circular cordon line around it with 32 control points. In addition, a screen line with 9 control points bisects the cordon, with vehicles crossing it in any direction being charged. (Through traffic can still pass through the city without charge via certain by-pass routes). Only one charge is made each day regardless of origin or destination -- thus the concept of a day fee levied from 6 a.m. to 6 p.m., Monday through Friday. The proposed day fee of *SEK25* [*US\$4.22*] -- which is much higher than a revenue-maximizing fee in order to combat congestion -- is expected to curtail traffic by a fifth. In contrast to other systems such as the Trondheim system, in which transponders for local residents are given away free, each local motorist desiring to enter inner Stockholm is required to purchase a transponder at manufacturer's cost, estimated to be *SEK100* [*US\$16.89*] a piece. About nine tenths of motorists are estimated to be driving with purchased transponders, whereas a tenth of motorists are enforced via the video recording system and charged by arrears if they are found to be without rental transponders. It was hoped that technological development would be able to verify pictured license plate numbers electronically rather than manually. With average daily traffic of 195,000 cars and 260 operating days a year, the system cost per transaction is *SEK0.69* [*US12.7 cents*] in 1990 figures, which is higher than that of a simple AVI system for toll roads but lower than that of a combination AVI and manual system.

Because the electronic fee system was estimated to take a couple of years from implementation to operation, the City of Stockholm proposed a manual zone fee system, i.e., supplementary licensing, in June 1989 to serve during the transitional period (City of Stockholm, 1989b). The supplementary license was set at the same rate as that proposed for the electronic system, that is, *SEK25* [*US\$4.22*] a day. In addition, a

monthly car card of SEK300 [US\$50.68] is available. It was estimated that at least 50 traffic wardens were required to monitor the nonstop traffic and a degree of compliance of only 75% was expected due to enforcement problems. The cost per transaction of SEK1.97 [US36.4 cents] in 1990 figures for the manual proposal is considerably higher than that of the electronic proposal a couple of months earlier.⁵⁴

In Autumn 1990, a bill was placed before the Swedish Parliament to introduce road pricing in Stockholm on an experimental basis from January 1991 to June 1993. As a result of higher petrol prices around the time of the Gulf war, and reservations about the manual zone fee proposal, the road pricing experiment was deferred until an acceptable electronic system that could protect privacy becomes available.

A2.2 The Dennis Package, 1991-92

In January 1991, the three political parties in the City and County of Stockholm, who form a two-thirds majority in Parliament, signed an agreement on traffic and the environment known as the Dennis agreement.⁵⁵ They agreed that major investments totalling SEK28 billion [US\$4.73 billion] will need to be spent -- half of them are for public transport and the other half are for ring roads around Stockholm. What they had left undecided was the issue of whether or not to implement road pricing in Stockholm in 1997 and, in the Gothenburg area in 1994 (Ministry of Transport and Communications, 1991). The Swedish Parliament has adopted the principle of marginal social cost pricing -- including congestion, environment, road maintenance and accident costs. For the Stockholm region, the marginal social costs for car traffic alone are estimated to be SEK 10.0 billion [US\$1.69 billion] in 1990, of which SEK2.5 billion [US\$0.42 billion] -- only a quarter -- is collected (Tegnèr, 1991). Fully three quarters of the total marginal costs are composed of congestion costs (42%) and accident costs (35%). The annual net benefits of introducing marginal social cost pricing in the Stockholm region *and* combining the toll revenues with a package of ring road bypass extensions and public transport service quality improvements are estimated to be SEK8 billion [US\$1.35 billion] (Tegnèr, 1991).

In September 1992, the three political parties reached a final agreement regarding the adoption of road use charging as an instrument to finance road investments and public transport for the Stockholm Region, which costs a total of SEK35.9 billion [US\$6.06 billion] in 1992 figures (see The Social Democratic Party, the Moderate Party and the Liberal Party, 1992). To be introduced in 1996, the uniform toll for light vehicles (weighing less than 3.5 metric tons) entering the toll ring designed to surround the city of Stockholm will be SEK15 [US\$2.53] initially whereas the average toll will be SEK5 [US\$0.84] for both inbound and outbound trips on the West Link. For heavy vehicles, these so-called 'vehicle-use fees' will be three times higher (Malmsten, 1992). A total of about 25 toll stations will be situated on all roads leading to the city center and 2 toll stations will be located at the West Route. At the time of this writing, a combination of manual and electronic toll collection system -- as in the (24-hour) Oslo Toll Ring -- is planned. The fee system must be designed to satisfy the stringent requirements of security, anonymity, flexibility and the option of offering 'discounts'.

⁵⁴The annualized capital and operating cost and revenue figures are taken from Abbott (1990) whereas the rest of the data is from City of Stockholm (1989b).

⁵⁵The three major parties are the Social Democrats (which encompasses about 40% of Parliament), the Conservatives (25%) and the Liberals (10%).