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Chapter 4

CONGESTION PRICING TECHNOLOGIES: A COMPARATIVE EVALUATION

Satish V. Ukkusuri[1], Ampol Karoonsoontawong[2], S. Travis Waller[2] and Kara M. Kockelman[2]

[1] Department of Civil and Environmental Engineering, Rensselaer Polytechnic Institute, Troy, NY, 12180

[2] Department of Civil Engineering, University of Texas at Austin, Austin, TX 78705, USA

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ABSTRACT

The successful implementation of electronic congestion pricing is highly dependent on the identification and installation of appropriate technology. Several technologies exist in the market that differs according to vehicle tag type, transponder type, security strategy, cost and operating radio frequency. There are trade-offs with each technology, and very few studies presently exist that evaluate their performance under different conditions. Recent demonstration projects in Europe offer a unique opportunity to study key issues such as technology-related experiences, transactions, standardization and enforcement. This chapter discusses these experiences while identifying different performance criteria for evaluation. These performance measures are used in a formal evaluation framework based on the ELECTRE IV algorithm to rank different technologies. Such a framework complements the large body of work on congestion pricing, by providing an evaluation framework for streamlining technology investment decisions under different pricing schemes.

Keywords: Congestion Pricing, ELECTRE IV, Evaluation Framework, PRoGReSS Project, Technology.

1. INTRODUCTION

The past several years have witnessed tremendous impetus for deploying congestion pricing (CP) schemes in different countries worldwide. The recent interest in CP schemes is due to the advances in CP technology [TRB 1994]. There have been considerable methodological advances in CP modeling [see, e.g., Verheof, 2002; Hearn and Ramana, 1998; and Yang and Zhang, 2002]; however, there may be significant differences among practical applications. A recent thrust lies in determining the applicability of different pricing schemes and the potential hurdles that arise in planning such applications. There were three projects in California that were intended to demonstrate the benefits of CP. The Bay Bridge Project involved a differential peak/off-peak toll structure, but this was not pursued due to a lack of public support. The I-15 demonstration project near San Diego (1997) gave users the opportunity to move from regular lanes to less congested high-occupancy vehicle (HOV) lanes by paying a toll. The operator was required to maintain at least a level of service B in the HOV/HOT lanes. This demonstration project, which ended in December 1999, was deemed successful [FHWA, 2001] as it was self-sustaining and achieved its prescribed goals. The pricing of a privately financed toll road in 1995 on State Route 91 in Orange County, California is the third such project in that state. The private operator used differential pricing schemes based on time of day and traffic levels. Tolls were collected via Automated Vehicle Identification (AVI) transponders. All vehicles with transponders and a pre-paid account were eligible to use the lanes. Despite the operational and political issues surrounding the project, the private operator has a good customer base and is looking forward to expansion [FHWA, 2001].

Other ongoing and future U.S. demonstration projects will provide valuable information on technology implementation issues and the benefits of CP. Washington State's Puget Sound region has developed a phased approach for studying a possible pilot implementation. The key features of the pilot project are (i) in-vehicle GPS-based billing, (ii) system-wide pricing, and (iii) an experimental versus controlled research design. This pilot study is proposed to end in the summer of 2005. The Minnesota Department of Transportation (DOT) Pooled Fund Study plans to use On Board Units (OBUs) with GPS receivers. The GPS will collect distance traveled within the cordon. The tolls will be collected using Smart cards updated based on distance traveled. Many other states such as Oregon, Florida, New Jersey, and Texas are currently testing real world applications of different CP schemes. Relevant information about these projects can be found on the DOT websites.

An unresolved question in most of the demonstration projects is the identification of appropriate (inexpensive, effective and interoperable) technology for different congestion schemes. The recently concluded demonstration project in Europe (*PRoGReSS*) provides reliable information about experiences from different technology implementations. The results from these demonstration projects provide valuable information on operational, planning and policy related CP issues. Although, the experiences from *PRoGReSS* demonstration projects are not transferable to the United States, they provide important insights and implications. These demonstration projects themselves will prove the feasibility of the different technology implementations and developed theoretical models. A review of the literature shows very little discussion about how one might evaluate technology for different CP schemes. There are many dimensions to consider for evaluating technologies based on their costs, potential impacts and usefulness. The parameters for the evaluation process in this chapter are imputed from the technology experiences of these projects. As technology plays a pivotal role in CP implementation, a more detailed structure is needed to guide the evaluation of the demonstrations.

The purpose of this chapter is two-fold. Firstly, it reviews the technology related experiences from demonstration projects. The main purpose of this review is to augment recent technology implementation experiences rather than review CP technology which is covered in depth elsewhere [see, e.g., Spasovic et al. (1995) and Porter et al. (2004)]. Secondly, a framework to guide technology evaluation is presented. An important component in developing evaluation taxonomy is the identification of performance measures for the alternative technologies available based on different system needs. There are many considerations for this, including costs (both setup and operating), site characteristics (line of sight for visual sensors, power sources, reliability, communication medium, etc.), bandwidth requirements, administrative and billing needs, automated enforcement issues, security, privacy, and real-time communication requirements. A subset of these criterions is quantified for different technologies, based on the experiences from *PRoGReSS* demonstration projects. A state-of-the-art multi-criteria decision-making algorithm, the ELECTRE IV method is used to choose the best alternative. This is demonstrated on a set of alternative technologies and the robustness of the results is demonstrated using sensitivity analysis. The final section provides some concluding thoughts on the proposed approach.

2. SYNTHESIS OF CONGESTION PRICING TECHNOLOGY EXPERIENCES

CP as a concept has been in vogue for some time [e.g., Vickery 1959]. However, technologies to implement this did not arrive until the 1970's and have been evolving ever since. There are numerous Electronic Road Pricing (ERP) technologies now available, each with different capabilities and system architectures for distinct pricing applications. The literature provides substantial information related to ERP technologies [see, e.g., Pietrzyk and Mierzejewski (1993), Venable et al. (1995), Spasovic et al. (1995), Porter et al. (2004)]. The technology used in CP is highly dependent on the scheme in place. Various CP schemes have been proposed in the past depending on time of day and distance traveled. Gomez-Ibanez and Small (1994) classify them in seven basic forms: (1) point pricing; (2) cordon pricing; (3) zone pricing; (4) parking charges; (5) charges for distance traveled; (6) charges for time spent in the area; and (7) charges for both time spent and distance traveled. This synthesis aims at augmenting the previous reviews with recent developments and field experiences.

2.1. ETC – The Singapore Experience

Singapore began using ETC in 1998, in order to electronically monitor and manage vehicles entering a restricted zone, thus helping to ensure a smooth traffic flow. This system is capable of automatically imposing a demand-sensitive congestion toll on every vehicle without requiring drivers to slow or stop. One of the issues of the ERP systems tested in the mid 1980's was a concern over public privacy. Singapore, overcame the privacy and billing issues by using less intrusive systems with automatic toll collection. Details of this approach can be found in Langmyhr [1999]; it is similar to that used for Norway's toll ring. For example, entry into the restricted zone without an appropriate CashCard leads to an automatic fine of $40. A ticket is issued to each of the violating vehicles. Motorists insert a CashCard into the In-vehicle Unit (IU) when they are on the road. The IU costs about $90 and is installed in front of the driver's seat. The IU is programmed to connect to the computers on the toll gantries and the dynamic toll is automatically deducted. The IUs can be automatically swapped among vehicles and the toll is collected based on vehicle type [Langmyhr, 1999].

The ERP installation has had both positive and negative impacts on traffic flow. While it has been able to achieve uninterrupted traffic flow conditions during peak hours, the lack of accurate ERP changes based on the traffic conditions was observed to cause unnecessary bottlenecks in other parts of the road network. The automated system, while helping prevent bribery and forgery of CashCards, still has issues that concern the general public. Singapore's CashCards have to be placed into the IU 10 minutes before the first gantry in order to be able to properly communicate with the computers. The traffic agency responsible for this is opting for intelligent vehicles with incorporated ERP technology. However, this project is still in the development stage [Goh, 2002].

Although ERP has produced less revenue than manual systems in the short term, the Singapore government is confident that as travelers become familiar with ERP they will accept and use the system better [Goh, 2002]. To ensure success, the officials have identified that they need to upgrade the transportation system continuously. To complement the ERP system, a private bus system was proposed which has electronic display panels at major bus stops to inform passengers when the next bus would arrive. Alternative strategies for congestion management being considered by the Singapore government can be found in Goh [2002].

2.2. Experiences from Australia

ETC technologies have been recently implemented in the city of Melbourne after the Melbourne City Link Project (1996-2000). Multi lane free flow ETC was built and the tolling configuration is based on an open or screen line strategy, which permits future variations to be developed [Lay and Daley, 2002]. The ETC and the video enforcement were established by Combitech. The enforcement is by a video camera that captures the front identification number of each vehicle that passes under the gantry. When needed, the Optical Character Reader (OCR) records the registration number. If the tag transaction is successful, the video record is deleted. The system is designed so that any doubtful assignments are made in favor of the customers [Lay and Daley, 2002]. One important difference with the state of the art is that the OCR checking and customer bias procedures are done off-line, rather than in real time. The video does not allow car occupants to be distinguished.

2.3. Recent Demonstration Projects (Progress)

PRoGReSS is a demonstration project involving eight different cities in Europe for studying issues related to road pricing. It concluded recently, in May 2004, with experiences from eight different European cities. Information about these projects can be accessed at http://www.progress-project.org, from which the following information was obtained. The information presented here is mostly from technology experiences in the last year; older information about this project can be found in Porter et al. [2004].

I. Bristol

The main element of PRoGReSS in Bristol was not in the full implementation of the road pricing as anticipated originally. The primary focus was on a three-month technology trial between July and December 2003. Road user charging equipment was tested on a range of vehicles, from cars to heavy goods vehicles (HGVs). The demonstration involved the testing of Mobile Positioning Satellite (MPS) equipment and was based on cordon pricing of two of the main access routes into the city center. The equipment consisted of on board equipment (OBE), attached to the dashboard of the volunteer's vehicle, with a lead to the power source and the antenna on the roof of the vehicle.

Two technology trials were conducted in 1998 and 2000, which concluded that dedicated short-range communication (DSRC) works well as a technology. The recent GPS demonstration project in 2003 suggested that GPS does not (yet) work well and that many methodological and technical issues need to be resolved before it can be implemented on a larger scale. The main problem with the GPS systems was that they require a unit to be installed in all the cars, making them costly – both financially and operationally. Bristol is yet to take a final decision on the enforcement technology, but it most likely seems that it will be automatic number plate recognition (ANPR).

II. Copenhagen

The primary motivation for implementing CP in this city was to study mode shift changes. The entire area was divided into cordoned zones, and 500 voluntary test vehicles were equipped with GPS units to read the cordon rings and zones. The GPS display informs the driver of the charge level in the current zone and the total cost of the trip. The participants in the study belonged to heterogeneous income groups and commuting patterns and their car usage had to be for full time work. Two pricing schemes were implemented in the demonstration project: kilometer- (distance-) based charging and multiple zone pricing. Two different charging schemes were tested, resulting in three scenarios. Participants were paid money for their travel reductions. During the pricing period, the taximeter showed the amount to be paid based on the pricing scheme (cordon-and distance-based charging). These different pricing schemes were tested to study the influence of the method of payment on driver behavior.

The technology experience from Copenhagen is that GPS technology is necessary for distance-based pricing but may prove too costly for cordon pricing. The main problem identified with the GPS-based system is that all units have to be installed in the vehicles before the pricing scheme can be implemented. This is a costly exercise and, before such a system can be implemented on a larger scale; further work needs to be carried out relating to methodological, software and technical issues. However, an alternative technology – from an economic and organizational perspective – is to implement ANPR or DSRC technologies, which are proven to be cheaper and easier to implement. A key enforcement issue from this experience is that installing a nationwide GPS system is almost impossible because of the need to continuously monitor whether it is working when the car is turned on. Another possibility is to have mobile and stationary checkpoints.

III. Edinburgh (United Kingdom)

Based on trial pricing schemes implemented in October 2002 and February 2003, Edinburgh investigated two pricing schemes: single and dual cordon schemes. The former is a single cordon pricing around the city while the latter is a dual cordon around the city center and the city by-pass. In the technology trials, two sites were equipped with cameras and ANPR technologies. This system is similar to the electronic cordon pricing implemented in London.

The experiences at this site conclude that both transponder and ANPR-based technologies would be the best solutions for the considered pricing schemes. Based on this, the dual cordon-pricing scheme was selected as the preferred option. This design favors the ANPR-based technology, which does not require in-vehicle equipment. From the transactions point of view, the license purchasing scheme seemed to have performed well. One of the key enforcement issues was that lane-straddling was a bigger problem with ANPR technologies. It was also found that the overall level of successful reads could be increased by including both overlapping fields of view, and both front- and rear-facing cameras.

IV. Genoa (Italy)

A cordon-pricing scheme was tested to protect the historical city center and downtown in Genoa. This scheme covers a total area of about 2.5 km^2. The vehicles were charged at zone entrances; repeated entrances within a given time period were not charged. The pricing is dynamic, i.e., it varies according to the time of day, day of week, user type and environmental conditions. The technology is based on a roadside single-lane video camera; no OBU is used in this scheme. One of the primary reasons for selection of this technology is its cheap and easy to maintain. The ANPR technology is used which memorizes license plate numbers for every time period and this is sent to the central processing center where checks for exemptions are conducted and the charging is based on eligibility.

The main experience in Genoa is that, given state of the art, ANPR technology is quite good and affordable, but has an intrinsic rate of non-recognition. This value was reported approximately at about seven percent in the real operational environment. This might be overcome by integrating the ANPR technology with a transponder reader for frequent users. Enforcement was not observed to be a major issue in this case; the technology was designed to manage violations to the limited traffic zone. Standard municipal software for enforcement is already available for this specific purpose.

V. Gothenburg

The demonstration project in Gothenburg employed GPS-based equipment. The two scenarios considered include one that focuses on congestion in the morning peak with no fees collected during the other times of the day, and the other in which off-peak hours with different pricing schemes are considered. It was implemented with 350 volunteers where each vehicle is equipped with an OBU and GPS unit. The processor on the OBU uses location information to calculate the appropriate fee. The enforcement is external of the vehicles and is either through video or direct observation making a request for verification of payment made by the drivers.

The technology experience indicates that GPS systems are not sufficiently developed to be implemented in full-scale applications. The GPS technology did not perform to the satisfaction and needs certain improvements. Another observation from the experience is that the OBU functionality should be minimized due to cost and operational considerations. Transactions considerations led to the recommendation that there is a need to minimize the amount of information communicated to and from the vehicle. Two issues with enforcement were learned from this experience. Firstly, the control system for enforcement should be based on verification of performed payments and not on the OBU equipment functionality. Secondly, all the enforcement should reside outside the vehicle to increase the reliability of payment.

VI. Helsinki

The motivation for Helsinki to participate in this project is *not* to carry out a demonstration, unlike the other cities, but to perform a modeling study with a number of different scenarios for road pricing. The emphasis is more on organizing a stated preference survey and stakeholder interviews to study the potential behavioral impacts. This was done to bring awareness of CP as a demand management tool to the "key" authorities. Two schemes were modeled as part of the process, both the schemes are based on cordon pricing with distinct fee collection policies: passage-based and distance-based. The former system is an electronic fee collection system based on DSRC and a vehicle carrying a transponder. The latter scheme required an advanced OBU system like a GPS and a communication system to the central unit.

Technology related issues were not the focus of the demonstration project in Helsinki. The network impacts of the two CP schemes were studied; passage and distance-based. Since it is still unclear whether GPS technology will be completely feasible in the near future, it's still unresolved at to what technology should be used for distance-based pricing. Enforcement issues have not been considered explicitly in this process. It was concluded however, that enforcement would be realized fully using the ANPR technology.

VII. Rome

The main objective of pricing in Rome was to reduce the number of vehicles accessing the Limited Traffic Zone (LTZ) and to promote the use of public transport. In 2001, dynamic fair pricing has motivated the use of new technology. Enforcement of the LTZ occurs weekdays from 6:30 am to 6 pm and Saturdays from 2 to 6 pm. There were two independent technology systems used in the demonstration. The first one is the access control system, and the other is the payment system. This is based on the automatic toll collection system TELEPASS, which used a TV camera with infrared illuminators for OCR, a microwave transponder for DSRC with the electronic gate access and an OBU with Smart Card. The area covered by the system is around 4.6 km^2.

The technology experience from Rome was based on the DSRC technology in combination with the standard ANPR system using OCR technology. One limitation of this technology is that the electronic gate system neglects to detect a high percentage (roughly 15%) of vehicles entering the zone. This limitation was overcome by verifying the images taken before confirming the violation or checking with the OBU. The enforcement has significantly improved and has shown a constant decrease of about 10% after the activation with the electronic technology. The enforcement problem was high in special events, when the system was enlarged in time and the information was not communicated to all the citizens. This problem should be resolved by adoption of small variable message signs or special lights, to directly inform the drivers before they pass the gates.

VIII. Trondheim

A new tolling technology called AutoPASS was introduced in 2001 to complement the existing technology. The AutoPASS is an open standard system that is supported by Norway and is being proposed as a basis for standardization in Europe. The common method of payment is by a card called t:kort for all the transport services. This same card can be used for automated charging. These tags or OBUs are deployed in most of the vehicles in the city. A charge is levied when the vehicles leave the pricing zone.

The technology experience in Trondheim is very encouraging. After twelve years of operations all the components of the pricing scheme have an operating time of 99.98 percent or more. The standardization of the electronic fee collection has been the main goal of this demonstration project and is considered an important step in that direction. The procedure used for enforcement is based on taking video pictures of the violating vehicles. This is registered manually by an operator; this procedure was not automated because of the high investments needed in building an automated system.

In summary, most of the experiences in the PRoGReSS project relate to GPS-based units. GPS systems were tested in Bristol, Copenhagen, Gothenburg and Helsinki. Key recommendations from the study were (1) improvements to GPS technology are needed before it can be implemented on a large scale; (2) significant problems need to be solved before a GPS-system can be implemented full scale in urban areas; (3) the technology installation activity is quite enormous and expensive; (4) malfunction of the GPS unit, such as loss of battery power, and poor signal quality (especially during start-up), was noticed; (5) car malfunctioning is often blamed on new technology (experience from Copenhagen); (6) GPS is not distracting and its integrity is not a big issue for drivers; (7) these systems are not necessary for zone-based pricing, since they are required only for continuous monitoring. Other, less costly technologies like ANPR and DSRC can be used in this case.

3. TECHNOLOGY EVALUATION TAXONOMY

There are numerous technology alternatives for an organization wishing to pursue CP. Further, with the rapid strides in tiny technologies [Savran et al., 2002]; it is likely that technology options only will improve. An organization wishing to explore a particular CP scheme will be faced with the task of choosing an appropriate technology, potentially based on the list of performance measures provided in this section. These measures were developed from the perspectives of both the implementing agency and system users.

The problem of evaluation considered here relates to ranking different technologies based on absolute or relative values of the different performance measures. If these measures for a particular technology *X* are strictly dominated by technology *Y*, then the solution is trivial.

Additionally, the technology preference is clear if an over-riding constraint exists (such as budget limitations or lack of suppliers). In most situations, the decision-making is more complicated because no available alternative dominates. Many procedures for technology selection could exist, including negotiation, popular vote and cost-benefit analysis (CBA). Regardless of the context, an evaluation methodology like the one proposed here can help arrive at the final decision in a more defensible manner.

There is significant literature on evaluation techniques, to choose among a finite set of alternatives. CBA has frequently been used to set priorities; however, it has significant limitations [O'Leary, 1979]. It seems impossible that CBA can account various, sometimes conflicting criteria. This is due to the difficulty in assigning weights to the criteria (for example, criteria 7, 12, and 16, see table 2). Further, a major drawback of CBA is the lack of precise information on benefits and costs and the fact that this information is currently based on a wide variety of assumptions [Dixit and Pindyk, 1994]. A sensitivity analysis addresses some of these drawbacks. However, the analysis will be difficult due to the large number of parameters that can be varied in most problem formulations. Other methods that are directly derived from utility theory [Keeney and Raiffa, 1976] suffer from similar drawbacks. Roy and Vincke's (1981) review of the existing multi-criteria methods suggested that none overcomes these drawbacks. The ELECTRE II [Bertier and Roy, 1973] and ELECTRE III [Roy, 1978] methods lead to a partial pre-order; however, each criterion has to be weighted. The ELECTRE IV method was proposed as a more advanced option to overcome these limitations. Another method based on fuzzy set theory [Dubois and Prade, 1980] can be used to account for uncertainty in the criteria. However, this requires a much greater effort, and has not been found to fare better than the ELECTRE IV method [Roy and Hugonnard, 1982]. The ELECTRE IV method was used to rank suburban line extensions in the Paris Metro System, in the late 1970's. The final partial ranking was entirely compatible with the compromise achieved through the recognition of the different viewpoints of the various political and social groups. Due to its advantages and apparent success, the ELECTRE IV algorithm was used to evaluate CP technologies here.

3.1. Outline of the Evaluation Algorithm: ELECTRE IV

The ELECTRE IV algorithm essentially ranks a set of alternatives based on a number of factors (such as cost or ease of enforcement), which have been translated into some quantitative values that can be compared across all of the alternatives. Unlike many similar algorithms, ELECTRE IV does not require weights to be assigned to the different criteria, which avoids the problem of trying to quantify the relative importance of criteria that may be very different in nature. Instead, the modeler chooses which criteria are to be used to form outranking relations, and each of these is treated equally. Thus, essentially, all criteria have a form of equal "weight" when determining the weak and strong outranking relations (which are in turn used to form the ranks in the two ranking procedures). However, what is counted is the number of criteria with which one strongly or weakly outranks the other. The exact magnitude of the difference is of no concern as long as the strong/weak preference relations are the same. ELECTRE IV defines strict and weak preference relations based on each criterion – (For instance, Alternative A may be weakly preferred to Alternative B when considering costs, but Alternative B may be strictly preferred to Alternative A when considering ease of enforcement.) Based on these preference relations, the alternatives are ranked using two similar methods, and these ranks are averaged to form the final ranking of the alternatives, which is the output of the algorithm. Despite the significant theoretical work underlying ELECTRE IV, its application is straightforward once the threshold values that define the preference relations are chosen. It is this latter step which requires the most thought of those using the algorithm. For each criterion, one must decide by how much two alternatives need to differ to say that one is weakly (or strictly) preferred to the other.

Established without any weighting of the criteria, the ELECTRE IV method [Roy and Hugonnard, 1982] is based on three principles: pseudo-criterion, outranking relation, and partial pre-order. The term pseudo-criterion should be distinguished from a true criterion. For a true criterion, options are of equal merit when their criterion values are equal. Due to the imprecision inherent in the data, the concept of a pseudo-criterion is introduced based on indifference and preference thresholds. These thresholds can either be constant or relative, depending on the nature of the criteria. If the uncertainty, imprecision and indeterminacy grow with a criterion value, then the proportionality hypothesis is justified and the relative threshold should be adopted. Further, a criterion can be either a cost or benefit criterion. For a cost criterion, the lower the criterion value, the higher its merit and vice versa for a benefit criterion. Subsequently, we define the indifference threshold (q_k) and preference threshold (p_k) for benefit or cost criterion k. Note that, for both constant and relative thresholds, q_k and p_k are non-negative, and $p_k \geq q_k$. Denote the non-negative values of criterion k for options i and j as x_{ik} and x_{jk}, respectively. The definition of the relative thresholds follows [Roy and Hugonnard, 1982].

Options i and j are indifferent on criterion k if and only if

$-q_k \times x_{ik} \leq x_{ik} - x_{jk} \leq q_k \times x_{jk}$ for benefit criterion k; and

$-q_k \times x_{jk} \leq x_{ik} - x_{jk} \leq q_k \times x_{ik}$ for cost criterion k.

Option i is strictly preferred over option j on criterion k if and only if

$x_{ik} - x_{jk} > p_k \times x_{jk}$ for benefit criterion k; and

$x_{ik} - x_{jk} < -p_k \times x_{jk}$ for cost criterion k.

Option i is weakly preferred over option j for criterion k if and only if

$q_k \times x_{jk} < x_{ik} - x_{jk} \leq p_k \times x_{jk}$ for benefit criterion k; and

$-p_k \times x_{jk} \leq x_{ik} - x_{jk} < -q_k \times x_{jk}$ for cost criterion k.

For constant thresholds, the above definitions are still applicable by replacing the terms $q_k \times x_{ik}$ and $p_k \times x_{ik}$ by q_k and p_k, respectively.

The indifference threshold is employed to account for the imprecision and randomness affecting the input data. To determine such threshold on a criterion, we start from a positive value that is sufficiently small and non-significant, and gradually increase the value until it gets to a point considered to be the boundary of the difference. To determine the preference threshold on a criterion, we start from a sufficiently large value to ensure unquestionably strict preference, and gradually decrease the value down to the limit value so that the strict preference becomes questionable. This is the boundary between strict preference and weak preference. In our example application, it is considered more realistic to adopt constant thresholds for all criteria, and all considered criteria are cost criteria.

Next, we say that option *i* outranks option *j* when there is sufficient evidence from the comparison of all criteria. The rules for constructing strong and weak outranking relations are described in the following paragraph. The term “partial pre-order” is used to differentiate from the “complete pre-order”. A ranking structure is called a complete pre-order on a set of options if the ranking structure is a complete and transitive binary relation. For example, when the binary relation is the strictly preference relation ($\succ$), the complete binary relation means that for all pairs of options *i* and *j*, either option $i \succ$ option *j* or option $j \succ$ option *i*. For transitivity, option $h \succ$ option *i* and option $i \succ$ option *j*, implies that option $h \succ$ option *j*. Thus, the result from the ELECTRE IV method is a partial ranking that can contain a tie (a group of options with the same rank). The distillation procedure for constructing the partial pre-order is described in detail in the following paragraph.

The ELECTRE IV algorithm is divided into three stages: 1) construction of strong and weak outranking relations, 2) construction of downward and upward ranks by distillation procedure, and 3) determination of the final rankings. This algorithm is applied here to evaluate various CP technologies.

Stage 1.Construction of Strong and Weak Outranking Relations

Strong Outranking Relation (R_s)

Option i strongly outranks Option j (O_i R_s O_j) if and only if the following two conditions are satisfied:

1) For none of the criteria, O_j is strictly preferred to O_i.

2) The number of criteria on which O_j is weakly preferred to O_i (|J|) does not exceed the number of criteria for which O_i is weakly or strongly preferred to O_j (|K|). (|K|>=|J|)

Weak Outranking Relation (R_w)

A weak outranking relation can take place only in the absence of a strong outranking relation. Option *i* weakly outranks option *j* (O_i R_w O_j) if and only if at least one of the following two conditions is satisfied.

1) There is not some criterion *k* such that $x_{jk} > x_{ik} + p_k$, and $|K|<|J|$.

considering ease of enforcement.) Based on these preference relations, the alternatives are preferred to O_j for at least one half of the criteria.

Stage 2.Construction of Downward and Upward Ranks by Distillation Procedure

Both strong and weak outranking relations are used to construct downward and upward ranks. The distillation procedure is employed to construct such ranks. The output of this procedure is the ranking of each option *j* from the downward and upward distillation procedure. *V1(j)* and *V2(j)* represent the ranking of option *j* from the downward and upward distillation procedure respectively. *V1(j) and V2(j)* are obtained by the procedure described below. The difference between these downward and upward distillation procedure is explained as follows.

Downward Distillation Procedure

The following 10-step process is used for determining the downward rank (*V1*).

Step 0: Set $r = 1$

Step 1: From the strong outranking relation, determine strengths, weaknesses, and qualifications of all options. The strength of Option *j* is the number of options that are strongly out ranked by Option *j*. The weakness of Option *j* is the number of options that strongly outrank Option *j*. The qualification of Option *j* is its strength subtracted by its weakness.

Step 2: Find the maximum qualification and the number of options with the maximum qualification (*NUM1*).

Step 3:

- If there is only one option with the maximum qualification (*NUM1*=1), this option is ranked *r*.
- If there are more than one option with the maximum qualification (*NUM1*>1), every pair of these options is compared in the strong outranking relation.

  - If Option *j* strongly outranks Option *i* and Option *i* strongly outranks Option *j*, then both are ranked *r* ($V_1(j) = V_1(i) = r$).
  - If Option *j* strongly outranks Option *i* and Option *i* does not strongly outrank Option *j*, Option *j* is ranked *r* ($V_1(j) = r$).

Step 4: Find the number of options with the maximum qualification that are ranked (*NUM2*). If 0<*NUM2*<*NUM1*, then $r = r+1$.

Step 5: Compare the options with the maximum qualification in the weak outranking relation.

- If Option *j* weakly outranks Option *i* and Option *i* weakly outranks Option *j*, then if Options *j* and *i* have not been ranked, then both are ranked *r* ($V_1(j) = V_1(i) = r$).
- If Option *j* weakly outranks Option *i* and Option *i* does not weakly outrank *j*, and if Option *j* has not been ranked, then Option *j* is ranked *r* ($V_1(j) = r$).

Step 6: Find the number of options with the maximum qualification that are ranked (*NUM3*). If $NUM2<NUM3<NUM1$, then $r = r+1$.

Step 7: The options with the maximum qualification that have not been ranked are ranked *r*.

Step 8: If all options are ranked, stop. Otherwise, change the strong and weak outranking relations by deleting Options that are ranked.

Step 9: $r = r+1$, and go to Step 1.

Upward Distillation Procedure

The following 12-step process is used for determining the upward rank (*V2*).

Step 0: Set $r = 1$

Step 1: From the strong outranking relation, determine strengths, weaknesses, and qualifications of all options. The strength of option *j* is the number of options that are strongly out ranked by option *j*. The weakness of option *j* is the number of options that strongly outrank option *j*. The qualification of option *j* is its strength subtracted by its weakness.

Step 2: Find the minimum qualification and the number of options with the minimum qualification (*NUM1*).

Step 3:

- If there is only one option with the minimum qualification ($NUM1=1$), this option is ranked *r*.
- If there are more than one option with the minimum qualification ($NUM1>1$), every pair of these options is compared in the strong outranking relation.
  - If Option *j* strongly outranks Option *i* and Option *i* strongly outranks Option *j*, then both are ranked *r* ($RV2(j) = RV2(i) = r$).
  - If Option *j* strongly outranks Option *i* and Option *i* does not strongly outrank Option *j*, Option *i* is ranked *r* ($RV2(i) = r$).

Step 4: Find the number of options with the minimum qualification that are ranked (*NUM2*). If $0<NUM2<NUM1$, then $r = r+1$.

Step 5: Compare the options with the minimum qualification in the weak outranking relation.

- If Option *j* weakly outranks Option *i* and Option *i* weakly outranks Option *j*, then if Options *j* and *i* have not been ranked, then both are ranked *r* (*RV2(j) = RV2(i) = r*).
- If Option *j* weakly outranks Option *i* and Option *i* does not weakly outrank *j*, and if Option *i* has not been ranked, then Option *i* is ranked *r* (*RV2(i) = r*).

Step 6: Find the number of options with the minimum qualification that are ranked (*NUM3*). If *NUM2*<*NUM3*<*NUM1*, then $r = r+1$.

Step 7: The options with the minimum qualification that have not been ranked are ranked *r*.

Step 8: If all options are ranked, go to Step 10. Otherwise, change the strong and weak outranking relations by deleting Options that are ranked.

Step 9: $r = r+1$, and go to Step 1.

Step 10: Find the maximum of *RV2*. (*maxRV2*)

Step 11: *V2*(*j*) = 1+*maxRV2*-*RV2*(*j*); for all *j*.

Stage 3.Determination of the Final Rankings

The average values of *V1(j)* and *V2(j)* for each option *j* is used to determine the final rank [Goicoechea et al., 1982]:

$$MV(j) = 0.5 \times \left(V1(j) + V2(j)\right) \text{; for all } j$$

Note that more than one alternative can have the same rank; and other factors not included in the model can be used to resolve any ties.

3.2. Measures of Performance for Evaluating CP Technologies

There are various important measures for evaluating and comparing CP technologies. We divide these into four categories:

i. Economic Measures
ii. Operational Measures
iii. Impacts, Integration and Flexibility
iv. Other Measures

These performance measures represent the benefit of installation of a particular technology from both the operator’s and users’ viewpoints. Although, not entirely comprehensive, the measures listed below capture key evaluation parameters.

- Economic Measures:

Cost – This set of performance measures includes the overall installation, operation and maintenance costs. The overall cost of the technology can be measured in terms of the following parameters:

1. Technical life expectancy of the technology
2. Labor, operating and maintenance costs of the technology
3. Secondary costs incurred by placing the technology (e.g., are there any extra costs in construction, like street changes and increases in number of lanes)

- Operational Measures:

4. Reliability in detection of vehicles (other parameters could include how much time elapses between technology disruptions, their frequency, the ease of repair etc)
5. Ease of installation
6. Ease of replacement in times of failure
7. Simplicity of use
8. Ease of Enforcement

- Impacts, Integration and Flexibility:

9. Are there any traffic or environmental impacts associated with the technology?
10. Can the technology be implemented with the existing right of way?
11. How easy is it to integrate the proposed technology with existing technology?
12. Ease of integration with preferred or common payment methods (credit cards, AUTOPASS, debit cards etc)

- Other Measures:

13. Faith in credibility of the organization providing technology
14. Does the technology have any harmful effects on system users (e.g. does the technology affect the health and safety of the users?)
15. Availability of suppliers for that particular technology
16. How well do the technology providers handle privacy issues?

4. EXAMPLE DEMONSTRATION

In this section we demonstrate the ELECTRE IV algorithm on a subset of technologies that are commonly used in CP demonstrations. The different technologies used for evaluation are:

a. Manual Toll Booths (MTB)
b. ANPR – Automatic Number Plate Recognition

c. DSRC – Dedicated Short Range Communications
d. GPS – Global Positioning Systems
e. Infrared Communications (IR)
f. RFID – “smart” lost cost Radio Frequency Identification

It is important to note the difference between the RFID and DSRC technologies mentioned above. Historically both of these were the same. However, with the advent of 5.9 GHz band, these technologies have to be distinguished. DSRC is a subset of RFID. DSRC is claimed to deliver a far greater data rate and range to wireless highway applications. Compared with existing RFID toll applications, DRSC will deliver data rates of 25 Megabits per second, instead of 250 kilobits, and a range of up to 1 km, instead of 10 meters. This basic difference makes it possible for DSRC to offer a much higher data transmission speed than RFID does. Because of its long read-range, DSRC must be able to operate in a condition of multiple overlapping communication zones—a condition that most RFID systems today could not meet. Further, DSRC must also dynamically control such things as emitted power, channels and message priorities—things that current RFID systems cannot do. However, the RFID technology mentioned in (vi) is the next generation low-cost “smart” RFID systems that are currently being developed at the Auto-ID Center [Sarma, 2003; Juels et al., 2003]. The main features of this technology are the potential low cost of transponders (under $0.10) [Sarma, 2001], 13.56 MHz and 915 MHz ISM band in the US (which allows multiple reader-to-tag communication options) and better addressing of security and privacy issues [Jeuls et al., 2003].

The values of the identified performance measures are shown in table 1. These values are imputed from the most recent CP demonstration projects in Europe (PRoGReSS) as described in Section 2. Out of the sixteen criteria identified, we use the 10 best in the ELECTRE IV framework. These are arrived at by not considering criteria that have the same value for all technologies (e.g., criteria 14 and 15). Some of the other criteria for which the values could not be imputed from the demonstration projects were not considered in the evaluation. For this example we applied criteria 2, 3, 4, 5, 6, 7, 8, 10, 12 and 16. The constant indifference and preference threshold values are shown in table 2. A few key points need further elaboration. (1) Most of these criteria values are based on the recent demonstration projects in Europe (PRoGReSS) and past reports. For example, we know that ANPR/DSRC enforcement is better than both manual toll booths and GPS. A numerical value is imputed based on the demonstration projects. The values assigned are subjective, however, the robustness of the final results are verified by performing a sensitivity analysis. This is described towards the end of this section. (2) Some of the criterion values not known have been assumed in this study; however, with the availability of better parameters the model can be refined. For example, we do not know the enforcement for RFID but have assumed it to be good based on the information from recent research and other related applications [Juels, 2003]. (3) The values for the criteria 2, 3, 4 and 7 are measured on a relative scale (1 for best -10 for worst), whereas the criteria 5, 6, 8, 10, 12 and 16 are ordinal rankings from 1 (best) to 4 (worst).

Table 1. Values of the criteria for each technology

Technology /Criteria	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Manual Toll Booth (MTB)(1)	long	10	10	2	4	4	10	3	No	4	Not Easy	4	Good	No	Yes	1
ANPR (2)	long	3	7	6	2	2	4	2	No	3	Easy	2	Good	No	Yes	3
DSRC (3)	long	3	5	8	2	3	5	2	No	3	Easy	2	Good	No	Yes	3
GPS (4)	long	8	3	4	3	2	4	3	No	1	Not Easy	3	V.Good	No	Yes	4
Infrared (IR) (5)	long	8	3	3	3	3	3	2	No	2	Not Easy	2	Good	No	Yes	3
RFID (6)	medium	3	2	3	1	1	3	1	No	1	Easy	1	V.Good	No	Yes	2

Table 2. Values of the indifference and preference threshold for selected criteria with and without sensitivity analysis

Criteria	Indifference Threshold	Preference Threshold	Indifference Threshold (Sensitivity Analysis)	Preference Threshold (Sensitivity Analysis)
2	1	2	2	7
3	1	2	2	6
4	1	2	0	1
5	0	1	0	1
6	0	1	2	6
7	1	2	2	6
8	1	2	1	7
10	0	1	0	1
12	0	1	0	1
16	0	1	0	1

The results from the upward and downward distillation procedures after implementing the algorithms on tables 1 and 2 are shown in figure 1. The final rankings of the different technologies after the distillation process are shown in figure 1.

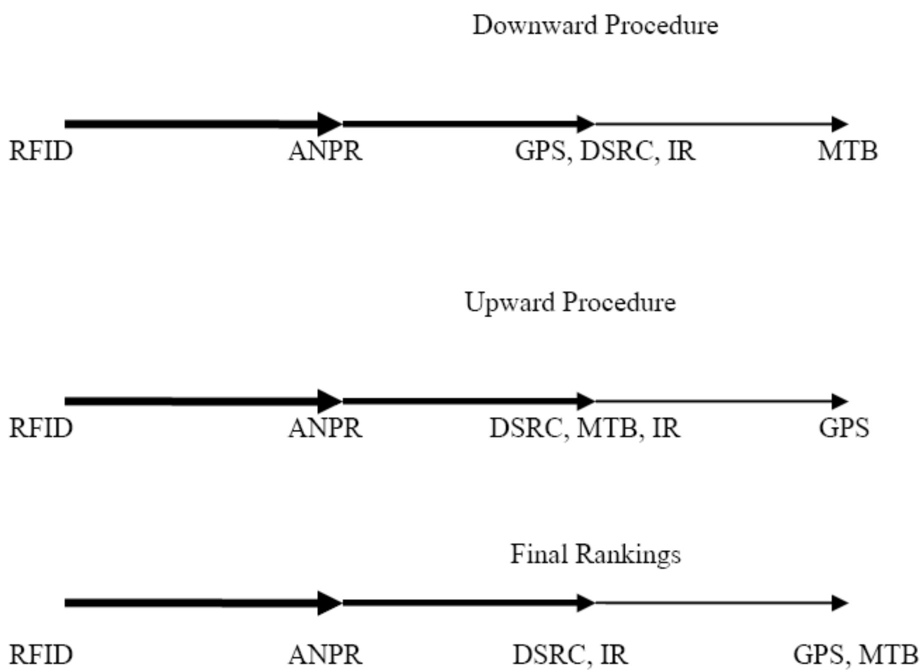

Figure 1. Outcome of the distillation procedure and the final ranking of CP technologies (Note: Link direction and line thickness indicate order of priority).

From the above assumptions of preference and criteria values, and analysis we conclude that the best technology among the alternatives evaluated is the "smart" RFID technology. This result is corroborated by recent studies suggest that the next generation of enabling technology is wireless technology with RFIDs [Sarma et al., 2003 and Zuckerman, 2004]. The next best technology is ANPR, which is ranked better than the GPS technology (as experienced in the PRoGReSS demonstration projects). It can also be observed that GPS performs poorly as compared to ANPR; however, all the technologies are at least as appropriate as Manual Toll booths. The results obtained here are consistent with the implementation experiences from PRoGReSS demonstration projects. Referring to figure 1, it is evident that to choose between DSRC and Infrared a value judgment (regarding the relative importance of the criteria) is needed. However, the results obtained are not the final word on the ranking of technologies. Significant uncertainties may exist in the criterion values (table 1). To account for this we performed a sensitivity analysis by considering the extreme thresholds for each criterion, as shown in table 2. We then substitute singly all the extreme thresholds for the base thresholds (table 2). This resulted in five new sets of values for the thresholds, in addition to the initial control set. Each of these six sets was processed through the four outranking systems (strong, weak, downward and upward), resulting in a total of 23 new partial pre-orders. For brevity, we discuss only the conclusions of this analysis.

Table 3. Final Rankings of the CP technologies

Technology	Option	Rank
Manual Toll Booth	1	4
ANPR	2	2
DSRC	3	4
GPS	4	3
Infrared	5	3
RFID	6	1

We observe that there is considerable stability in the rankings initially obtained, in all the 23 scenarios considered.

- In all the 23 scenarios RFID technology remains the most preferred technology. The rankings of other technologies change, but there is a consistent pattern to the results.
- In 14 scenarios MTB is ranked last while DSRC was ranked before MTB. This ranking is either reversed or there is a tie in all the other scenarios.
- The IR technology is consistently ranked second in 17 of the scenarios. In a few of the scenarios this place is taken by ANPR.
- GPS is ranked either third or fourth in most of the scenarios; their relative position fluctuates considerably.
- There are 4 scenarios in which the options 2, 3, 4 and 5 are ranked second.

The consistency of these results gives us sufficient confidence on the ranking of technologies and further sensitivity analysis is not required. Other intermediate results were analyzed which confirmed these same observations. The analysis of the scenarios appears to clearly validate the results mentioned in table 3. However, one important caveat is that considerations external to those mentioned in table 1 may modify some of the results obtained here. However, these criteria can be incorporated with the maturity of the decision making process.

5. Conclusion

This chapter synthesizes some of the experiences from recent congestion pricing (CP) demonstration projects around the world and provides a formal procedure for evaluating the appropriateness of various technologies. It also develops more precise measures of performance to evaluate the potential technologies that~~n~~ have previously existed. Quantitative and qualitative taxonomies identify a broad range of criteria for consideration in a comprehensive analysis. A state-of-the-art evaluation algorithm, ELECTRE IV, was used to evaluate several technologies overcoming many standard drawbacks of other evaluation approaches. The usefulness of the approach is illustrated on a subset of technology, some of which were tested in the PRoGReSS demonstration projects. The main insights of this evaluation are that: (1) given the performance measures (shown in table 1), RFID is the best technology to implement, though this does depend on the desired pricing scheme. (2) The subjective rankings of enforcement and privacy (provided in table 1) have significant impacts on the ultimate technology rankings. The implication from this insight is that technology that handles these issues better is more readily accepted and useful. (3) GPS will become the preferred technology if its cost, reliability and privacy issues are adequately addressed.

The evaluation's results (shown in table 3) corroborate the demonstration projects' technology experiences. Finally, the sensitivity analysis of the results demonstrates the robustness of the approach. We recommend that this evaluation framework can be used in planning other CP projects, and future efforts should concentrate on developing the criteria for these. Better technology investment decisions can be made with the evolution of the decision-making framework. As new technologies are developed, these can be added into the choice set to measure their efficacy.

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