Road Pricing[1]

The Department for Transport's Feasibility Study of Road Pricing in the UK[2] estimates that a well-targeted national road pricing scheme could achieve £10 billion worth of time savings a year. And indeed road pricing has had strong theoretical support over many decades. So what's the problem with implementing road pricing? What are the challenges, and, in particular, what technology, economic and network modelling issues need to be overcome to make it happen?

Increasing congestion

In the last thirty years our disposable incomes have more than doubled, the cost to the user of public transport has nearly doubled, and the cost to the user of motoring has remained approximately constant – all measured in real terms. On economic efficiency grounds, the cost to the user of roads is too low overall, especially on congested roads at busy times, and sometimes too high, mainly in rural areas.

The levers currently available to Government are too blunt to address the problem of increasing congestion. Rail and bus subsidies are partly motivated by their effect on road congestion, but the linkage is distinctly indirect, and it is by now clear that even lavish public transport will not alone solve road congestion. Fuel duty is an excellent instrument to tackle CO_2 emissions but it cannot target congestion, which affects a relatively small part of the road network for only part of the day. And capacity expansion where possible is not enough, because induced traffic would make congestion even worse in those areas where capacity increase is prohibitively expensive in financial or environmental terms.

Congestion pricing?

Might congestion charges, varied by road and time, be the way forward? William Vickrey[3] was the first to propose a system of electronic tolling to deal with urban congestion, in 1959 in work on the Washington metropolitan area. Vickrey made a detailed study of the engineering of congestion pricing, and proposed that each car would be equipped with a transponder whose personalised signal would be picked up when the car passed through an intersection, relayed to a central computer which would calculate the charge according the intersection and the time of day, and add it to the car's bill.

Vickrey made a persuasive presentation on congestion pricing to the UK's Ministry of Transport, which led to the setting up of a panel on road pricing, and thus to the

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[1] This is an abridged version of an article first published in Ingenia 29 (2006) 34-40; the author is grateful to the Royal Academy of Engineering for permission to reproduce the material. The full version of the article is accessible at www.ingenia.org.uk/ingenia/issues/issue29/kelly.pdf .

[2] Department for Transport. 2004. Feasibility study of road pricing in the UK. Available from www.dft.gov.uk .

[3] Vickrey's first degree was in Mathematics and Electrical Engineering from Yale, and he shared the Nobel Prize for Economics in 1996. In his ideal world, engineering economics would occupy a position of prominence and efficient pricing would be a central element of good engineering practice.
R. Arnott, William Vickrey: contributions to public policy. International Tax and Public Finance 5(1998), 93-113.

celebrated Smeed Report of 1964. The Smeed Report supported the principle of congestion pricing and noted that several technologies – with further development – could be used to implement it.

Forty years later the technologies of road pricing have moved on, the limitations of existing policy instruments have become apparent, and the economic damage of congestion is rapidly increasing.

Pay as you drive

In a recent article Hills and Blythe[4] have reviewed the technologies available for implementing road user charging. Microwave-based digital short-range communication (DSRC) systems are the modern successor to Vickrey's scheme. These systems need road-side beacons typically mounted on a gantry, with electronic tags, possibly supporting a smartcard, in vehicles. Examples are the Singapore area-based system, the Stockholm congestion tax and the E-Z Pass in widespread use on toll roads in the US.

Wide area communication-based systems are a more recent innovation. These systems use two technologies adapted from other applications, satellite based positioning and cellular radio communications links, and need no road-side infrastructure. Examples include the German truck toll and Norwich Union's pay-as-you-drive insurance. Both tag and beacon and wide area systems require a separate enforcement infrastructure, generally based on cameras and automatic number plate recognition (ANPR) technology.

The London congestion charge relies for enforcement on ANPR cameras to identify vehicles within the charging zone. Crucially, it requires no in-vehicle equipment. Instead motorists using the zone have until the next day to pay by one of a variety of means: at retail outlets, by post, by telephone, by text message from a mobile phone or via the web. Chargepayers thus have access to a number of payment channels. This helped with public acceptance initially, and has allowed users to migrate over time to the more automated payment channels. Indeed there now seems scope for further automation, to allow technologies such as those described earlier to assist with self-declaration.

Getting to know you

Privacy is a critical issue since charges, if they are to target congestion, need to be specific in space and time. Our attitudes in this area are evolving rapidly. Each time we use, or choose not to use, a mobile phone, an Oystercard or a Tesco clubcard we learn a little more of our own individual trade-off between personalisation, convenience and privacy. And as more and more personal data is collected, the focus of the privacy debate is moving from data collection to higher-level questions on data access and the algorithms which can search and correlate across databases.[5]

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[4] P. Hills and P. Blythe. 2002. For whom the road tolls? Ingenia 14, 21-28.

[5] Data Mashing. Foundation for Science and Technology Journal 19:2 , 14-17.

The underlying technologies, of smartcards, wireless communication, ubiquitous computing, global positioning, and our acceptance of them are driven by fast moving consumer markets. In such a dynamic environment it no longer seems feasible for government to mandate and specify a black-box for every car. A more promising approach would be to encourage local road pricing schemes that meet local needs, where government chooses the charge, but where payment is allowed by a choice of technologies, run by a variety of providers.

Payment mechanisms could piggy-back on existing services, for example, pay-as-you-drive insurance, or satellite navigation, or breakdown service, or could offer new opportunities for market entry. Innovation would be encouraged in equipment, back-office, business process and marketing, forcing down costs. As road pricing extends outwards over larger and larger regions we could expect mechanisms to evolve, perhaps through self-declaration to tag-and-beacon and then on to satellite. A user could choose her own pace of progress, which would likely depend upon her driving patterns and personal preference.

Predicting the consequences

The variety of technologies now available for road pricing force us to recognise that technology alone is not delaying the introduction of road pricing. The Feasibility Study of Road Pricing identified several areas of uncertainty, with the most challenging for government concerning how prices would be set and how revenues generated would be invested. It is a major modelling challenge to assess the effect of such decisions, and it is worth looking in a little detail at why this is.

In congested networks the pattern of traffic flows through different parts of the system is the consequence of a subtle and complex interaction between different users. For example, in a road network we should expect each driver to attempt to choose the most convenient route, and this choice will depend upon the delays the driver expects to encounter on different roads; but these delays will in turn depend upon the route choices made by others. This mutual interdependence must be taken into account to predict the effect of changes to the system, for example the construction of a new road, or the introduction of tolls for parts of the system.

The basic theory of flows in congested road networks was developed by Wardrop and Beckmann[6] in the 1950s. Their work showed that in a congested network the volumes and patterns of traffic resulting from individual users attempting to do the best for themselves will deviate systematically from a social optimum. Essentially a driver is influenced by the delay she incurs, but is oblivious to the additional delay she causes to others (called the externality, or marginal social cost).

For the case where the value of time is the same for all drivers, and where a toll can be charged on each link of the network, the problem has a neat mathematical answer:

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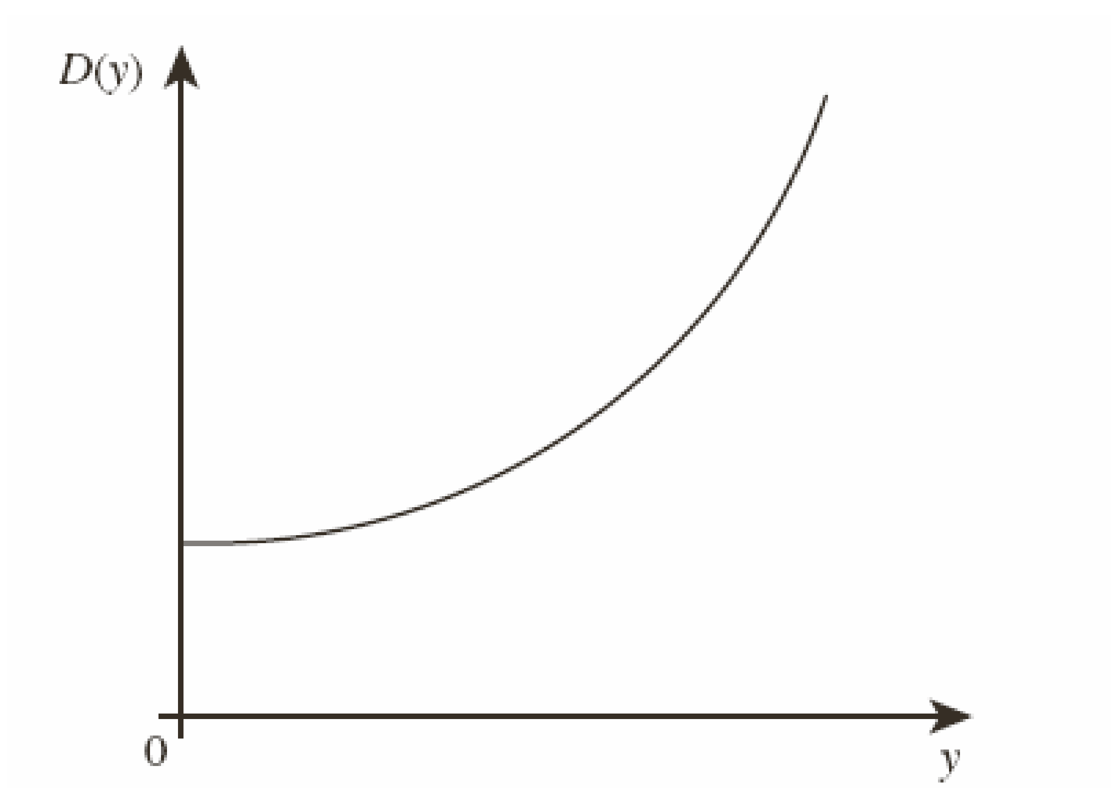
[6] Beckmann, M., McGuire, C.B. and Winsten, C.B. 1956 Studies in the Economics of Transportation. Cowles Commission Monograph, Yale University Press.
Wardrop, J.G. 1952 Some theoretical aspects of road traffic research. Proc. Inst. Civil Eng. 1, 325—378.

Journey times and congestion



The time taken to travel along a link, $D(y)$, expressed as function of the total flow y along the link. As the flow increases, congestion effects cause additional delay.
At small values of the flow y the delay $D(y)$ is just the time taken to travel along an empty road; for larger values of y the delay $D(y)$ is larger, and quite possibly *much* larger. Each additional vehicle suffers a delay itself, but by increasing the flow it also increases the delay for other vehicles. A similar relationship holds for junctions. The non-linear form of the relationship explains why congestion (the excess delay over and above that which would be experienced in uncongested conditions) may be substantially reduced with only a small decrease in traffic. The scenarios modelled in DfT's Feasibility Study of Road Pricing in the UK show a reduction in urban congestion of nearly half, with about a 5% reduction in all traffic: a shift of a small amount of traffic from busy roads at peak times (to other times, or to other roads, or to car sharing) has a substantial impact on congestion.

The graph shown above is single valued. It is quite possible for the curve representing delay as a function of flow to bend back upon itself, so that higher delays than shown in the graph correspond to flows *smaller* than the maximum flow shown there. You are in this part of the graph when you experience stop–start driving conditions on a congested but otherwise incident-free motorway. Part of the aim of demand management is to keep flows and delays away from this part of the graph. Other forms of demand management for motorways include ramp-metering (traffic lights to regulate flow on slip roads) and High Occupancy Vehicle lanes.

a toll on each link, determined locally from the delay characteristics and traffic at that link, is sufficient to shift the user equilibrium to the system-wide social optimum. In mathematical terms, the optimization is a convex problem: optimum link utilisations are uniquely determined and vary continuously with changes in the form of the network.

However if values of time are heterogeneous or if not all links can be tolled, then the mathematical problem becomes non-convex and harder: there may be several radically different candidates for the system optimum, with slight changes in the network specification causing one or other to be preferred. As a very simple example, two roads between the same two towns might in general have *different* tolls. The intuition is as follows: with different tolls, a driver can choose the more expensive and less congested route on the occasions when time is important to her, and this ability to choose provides benefits both for her and others. Having different tolls is better than having equal tolls on the two roads. Similarly the driver choice provided by HOT lanes in the US has contributed to their popularity.[7]

The big picture

The road network is part of a wider transport network, and the transport network is part of wider economic system. So the overall optimization problem needs to respect the interactions between transport modes, and between transport and patterns of commuting and land use. Again non-convexities arise, as is common in most areas of network planning, from telecommunications to power grids.

Our current transport systems are so far from economically efficient that there may well be unexpected consequences from a regime that allows users to see more clearly the real costs of travel. For example, what might be the consequences for the railways and for land-use? Our current patterns of transport and land use have developed over decades or even centuries, as the road and rail networks and the distribution of our population have co-evolved. With road pricing, patterns of travel will change more rapidly, as has been evidenced with London's Congestion Charge.[8]

The amount of time spent travelling and the fraction of income devoted to transport vary substantially from individual to individual. However, averages over a population have been remarkably stable over a very wide range of geographical and cultural settings, historical periods and transport technologies[9]. As technologies have

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[7] In the US, many High Occupancy Vehicle lanes are being converted to High Occupancy Toll lanes, accessible to motorists driving alone if they pay a toll. The tolls on the I-15 in San Diego is recalculated every six minutes, taking into account upstream traffic flows, and then posted some distance ahead of the tollway entrance, giving drivers time to choose whether to use the tolled or free lanes. On normal commute days the toll ranges between 50 cents and $4, but can be raised to $8. The toll is set to allow free-flow conditions, and hence maximum throughput, on the tolled lanes. Reliability as well as time has value, and some studies indicate a higher value of reliability for women than men, possibly because child-care responsibilities reduce their scheduling flexibility. This may explain the consistent finding across many studies that, other things being equal, women are more likely than men to choose the tolled road or the HOT lane. D. Brownstone and K A. Small 2005 Valuing time and reliability: assessing the evidence from road pricing demonstrations.

[8] Transport for London: Impacts monitoring, and technology trials. Available from www.tfl.gov.uk .

[9] A. Schafer and D.G. Victor 2000 The future mobility of the world population. Transportation Research A34(3), 171-205.

advanced and our incomes have increased, we have travelled faster and further. If we are exposed to the real costs of travel, without implicit or explicit subsidies, will we continue to travel so much further with each generation?

Taking the plunge

Despite the issues of non-convexity, and the uncertainties over the evolution of land use and rail, it is clear that road pricing’s time has come. The substantial impacts on everyday life suggest that we need an adaptive approach to its introduction, with close monitoring of the impacts of the early schemes. Government has an important role to ensure interoperability at the commercial level – a start should be interoperability of the tags for the Dartford Crossing, M6 Toll and Severn Bridge, all of which use DSRC at 5.8 GHz.

A likely progression for users is self-declaration, as in the central London scheme, through installation of an interoperable DSRC tag, to satellite technology, as the market discovers the potential of locational services. Fine-grained timed data on location will continue to raise privacy concerns, which will be mitigated to some extent by allowing users a choice of technology and service provider. The prize for a society able to make the progression through to widespread road pricing will be a transport system able to cope with the demands of a sophisticated and flexible modern economy.

Biography – Professor Frank Kelly

Frank Kelly FRS has held positions in the Engineering and Mathematics Faculties at the University of Cambridge, where he is currently Professor of the Mathematics of Systems. His interests focus on methods of self-regulation for large-scale systems. He has received several awards for his research on networks, including the Lanchester Prize of the Institute for Operations Research and the Management Sciences, and the Kobayashi Award of the IEEE. He has recently completed a three year term as Chief Scientific Adviser to the Department for Transport.