TSINGHUA SCIENCE AND TECHNOLOGY
ISSN 1007-0214 11/16 pp339-350
Volume 11, Number 3, June 2006

Socio-Economic Impact Assessment of Intelligent Transport Systems*

JUAN Zhicai (隽志才)**, WU Jianping (吴建平)†, Mike McDonald†

Institute of Transportation Studies, Shanghai Jiao Tong University, Shanghai 200052, China;
† Department of Civil and Environmental Engineering, University of Southampton, Southampton SO17 1BJ, UK

Abstract: A general review of the socio-economic impact of the intelligent transport system (ITS) is presented with a case study to demonstrate the data envelopment analysis method. Cost-benefit analyses are still the dominant method for evaluating ITS and other transport engineering projects, while cost effective analyses and multi-criteria appraisals are widely used to define and prioritize objectives by providing useful information for the most promising policy decisions. Both cost-benefit analyses and a data envelopment analysis method are applied to analyze the socio-economic impact of convoy driving systems. The main findings are that a convoy provides a worthwhile benefit-cost ratio when more than 30% of the traffics in the convoys and the traffic load exceeds 5500 vehicles/h for a three-lane motorway. The results also show that for a fixed percentage of convoys, increased demand will increase the data envelopment analysis method relative efficiency and that the neglect of certain output indicators of an ITS may result in underestimation of the system effects.

Key words: socio-economic impacts assessment; cost-benefit analysis; data envelopment analysis; intelligent transport system; convoy driving

Introduction

With the rapid increase of road traffic congestion in recent years, many intelligent transport systems (ITS) have been developed and applied throughout the world[1-3]. ITS can improve road transport, driver support, and mobility. Potential investments in ITS will grow quickly in the near future.

Appraisals of ITS projects should include technical assessments, user acceptance assessments, traffic impact assessments, environmental impact assessments, and socio-economic assessments[4,5]. However, many ITS assessments have focused only on one or perhaps several of these areas[6,7] with relatively fewer analyses of the socio-economic effects.

Socio-economic assessments are particularly important for government policy decisions with a considerable amount of work now and in the past being conducted to develop suitable evaluation guidelines in Europe and the United States for ITS projects[8]. However, most guidelines do not detail how the impacts should be measured or valued with many benefits being inherently difficult to measure or even define in an agreed manner. Considerable efforts have been made to identify the range of potential benefits with less emphasis on the costs. Also, as different projects have often adopted different guidelines and cost and benefit evaluation methods, the results are often difficult to compare.

Bristow et al.[9] reviewed various appraisal procedures used to evaluate ITS projects and suggested that ITS project appraisals need to have the same form,

---

Received: 2004-11-26; revised: 2005-09-20

* Supported by the National Natural Science Foundation of China (No. 50378042) and the Engineering and Physical Science Research Council in the UK (No. GR/M99811)

** To whom correspondence should be addressed.
E-mail: zcjuan@sjtu.edu.cn; Tel: 86-21-52301396

level of sophistication, and consistency as appraisals of conventional transport infrastructure investments. The paper argues that appropriate methods have not yet been established which in turn poses a number of challenging questions, since current socio-economic evaluation procedures are not directly suitable for either measuring or evaluating many of the impacts that ITS schemes are implemented to achieve.

The most common assessment methodologies for socio-economic assessments are cost-benefit analyses (CBA), cost effective analyses, and multi-criteria appraisals, e.g., data envelopment analyses (DEA). These methodologies are used to assess the socio-economic impacts of ITS in this paper.

1 Cost-Benefit Analyses

Cost-benefit analyses were developed from the basis of welfare theory. Such analyses estimate the ratio (or difference) between the benefits and the costs of an application considering a specific time period (e.g., 20 years) and spatial dimension (e.g., a motorway corridor). Both the benefits and the costs incurred in future years are discounted by an appropriate rate. Cost-benefit analyses have been widely applied to project appraisals of both ITS and conventional transport infrastructure projects, where both the benefits and the costs can be quantified.

1.1 Cost-benefit analyses of an automated highway system

Ran et al.[10] used cost-benefit analyses to assess the impact of automated highway systems. The system costs included the cost of the roadway infrastructure, the traffic management centre for system operation, and the physical construction. The annual expenditure for the roadway system was estimated to be \$ 3 082.40/(y • peak-h • mile); the cost of the traffic management centre operations (recurring and nonrecurring) to be \$ 3 211.30/(y • peak-h • mile); and the cost of the physical infrastructure construction, including construction of the earthen works, retaining walls, bridges, pavement, drainage, etc., to be \$ 158 378.70/(y • peak-h • mile) to \$ 130 936.70/(y • peak-h • mile). A 6% discount rate was used.

The road user cost included fees for the in-vehicle equipment, including systems for vehicle lateral control, vehicle longitudinal control, vehicle route guidance, and communication with the roadside automated highway systems. The estimated cost for the in-vehicle equipment of each vehicle was \$ 26.7/(y • peak-h • mile).

Time saving was considered as the only benefit in the assessment. Speed-flow-density, relationship for the system with both 100% and 0% automated traffic were used to develop simplified relationships for the speed, density, and flow for the 20%, 50%, and 80% automated traffic mixtures. The annual benefits of time savings were then calculated for each scenario (i.e., different percentages of automated vehicles) considering 250 d/y, 6 peak-h/d, and \$ 10/h for journey time saving. The conclusions showed that when different proportions of automated and conventional vehicles operate simultaneously on an automated highway system, the net benefits in capacity and journey time saving increase in proportion to the automated traffic since the operating costs are shared by more entities. The total cost was lowest for the 80% automated scenario because of the increased capacity.

Baum and Geissler[11] also used a cost-benefit analysis to assess the CHAUFFEUR project, a driver assistance system for the road transport industry. With the CHAUFFEUR system, trucks are coupled electronically and carry out autonomous driving functions. The core application of the CHAUFFEUR system is two trucks that are coupled electronically (Tow-Bar). As the lead truck is driven conventionally, the trailing truck follows automatically. Therefore, the driver in the trailing truck is relieved of driving tasks, such as lane keeping, speed, and distance adaptation. In early 1999, the Tow-Bar application was successfully demonstrated on German motorways[12].

In their paper, Baum and Geissler presented a general methodological framework to assess the social costs and benefits of a general automated highway system as illustrated by the CHAUFFEUR system. Their main focus was the assessment of benefits using a traffic simulation model that enabled evaluation of the benefits from the traffic effects. The model results were then input into a cost-benefit analysis which indicated that the CHAUFFEUR system could lead to significant benefits for society.

1.2 Cost-benefit analyses of advanced travel management systems

Schnarr and Kitaska[13] assessed the advanced travel management system (ATMS) in the Greater Vancouver area of Canada over a 30-year period. The benefits considered included reductions in travel time, accidents and fuel consumption, regional economic development, and system reliability. Costs included capital, operating, and maintenance costs of the system as well as any offset costs due to potential changes in revenue streams.

The results show that ATMS is a worthwhile investment for the province from a socio-economic perspective. The thirty-year benefits were conservatively estimated as \$ 2.0 billion-3.8 billion against total costs of \$ 113 million in present value dollars with a benefit-cost ratio of 18:1 to 33:1. The benefits were predominantly travel timesaving, which accounted for 72% of the total quantified benefits.

1.3 Cost-benefit analyses for vehicle information and communication systems

Shibata[14] presented a cost-benefit analysis for a vehicle information and communication system. The benefits considered were avoidance of ‘stray driving’ and optimal route choice. The costs and benefits were compared using diffusion curves for the technology to show breakeven points at different prices for the products. The expected benefits of the systems included: (i) reduced travel time; (ii) reduced fuel consumption; (iii) fewer accidents; (iv) reduced exhaust emissions; and (v) expansion of domestic demand/technological development. Only time and fuel savings were valued in the appraisal with no consideration of safety gains although accident reduction was one of the main aims of the project.

1.4 Cost-benefit analyses of variable message sign projects

Extensive survey work had been undertaken to evaluate variable message sign strategies in the Ile de France in the CITIES project[15]. The evaluation included user perception (based on comprehensibility, credibility, and utility rate), traffic effect, and socio-economic benefits. The socio-economic appraisal considered travel time savings and accident costs. This is one of the few economic appraisals of a system in operation. The advantage of this study is the existence of a large functioning variable message sign system covering a 500-km motorway network. It provides results relating to actual rather than hypothetical benefits.

Tarry and Graham[16] also evaluated the impacts of variable message signs on the M40 in the UK. The assessment considered vehicle operating cost savings due to varying distances of alternative routes. The estimated saving was approximately ￡68 000/y against a capital cost of approximately ￡150 000.

1.5 Cost-benefit analyses of ITS in the UK and USA

Jeffrey[17] used cost-benefit analyses to explore the potential benefits of a route guidance system operating throughout Great Britain. The benefits considered included operating cost savings, time savings, and accident reductions.

Harvey[18] estimated the potential benefits of intelligent vehicle and highway systems in the USA and UK. The annual cost to the USA economy of highway inefficiencies (e.g., congestion, accidents, and navigational waste) was estimated to be around \$ 300 billion. Assuming that the system could reduce these problems by 15%-20%, i.e., an annual saving of \$ 45 billion-75 billion, the expenditure required to secure such returns was predicted to be \$ 209 billion by the year 2011. For the United Kingdom, the predicted benefit from dynamic route guidance systems and urban demand management systems was expected to be in excess of ￡1 billion/y.

1.6 Cost-benefit analyses of travel information systems

Lee[19] used a cost-benefit analysis to analyse the benefit of the website-based traveller information system in Washington’s State Department of Transport. The traveller information system provided the real-time traffic conditions on expressways and major arterials. The potential benefits were time and cost savings for the users as a result of informed travel choices, increased user confidence in travel choices, and reduction in congestion, pollution, and other external costs. The limitations of the assessment were that little information is available for how often users alter their travel behavior in response to the information and how much the information is worth, either to users or to the transport system.

2 Other Assessment Approaches

Besides cost-benefit analyses, cost effective analyses and multi-criteria appraisals are often used for ITS socio-economic impact assessments. In a cost effective analysis, costs are determined in a monetary unit while the impacts are measured first in various units, and then transferred into a single relative scale. The system total effectiveness is determined by the following equation:

$$E = \sum E_j W_j = \sum F_j(I_j) W_j,$$

where E is the total effectiveness; E_j is the effectiveness of unit j; W_j is the weighting factor; I_j is the indicator related to effectiveness of unit j, and F_j is the value function transforming the indicator into the effectiveness of unit j.

The effectiveness for each alternative is determined and used together with the estimated cost as the basis for making a decision as to which alternative will be selected for implementation. Multi-criteria appraisals deal with discretionary or less tangible impacts that cannot reasonably be expressed in monetary units. The different criteria included in a multi-criteria appraisal can be combined to determine a single value (as in cost-benefit analyses). Data envelopment analysis, originally proposed by Charnes et al.[20], is one type of multi-criteria appraisal which is commonly used to estimate multi-output production functions and to measure productive efficiency. Data envelopment analyses make no assumptions for the mathematical form of the production function and do not utilize prices to aggregate either outputs or inputs. Therefore, it is exceptionally suited for efficiency analyses, where products are difficult to represent in a monetary value. Data envelopment analyses have often been used to select projects from a group of candidates[21,22], and to evaluate the efficiencies of alternative transport systems[23-26].

2.1 Cost effective analyses of intelligent transport systems

Taylor and Singleton[27] examined options for extending the intelligent traffic control system in Plano, Texas, using a cost effective analysis approach based on the present value of costs over various time scales. They considered eight aspects of costs, timing, and performance for each of five alternatives. Each option was then ranked with the best performer obtaining 5 and the worst 1, with a weight to show its relative importance. Finally, a weighted score was derived for each option.

De Corla-Souza et al.[28] examined transportation alternatives, including those incorporating technologies, using a ‘least total cost approach’. The advantages with this type of appraisal were that it allows comparisons of transportation investments across modes and comparison of major investment alternatives with management alternatives.

2.2 Cost effective analyses of advanced vehicle monitoring and communication projects

Daetz and Bebendorf[29] reported a socio-economic impact assessment for the mass transport system in Los Angeles, involving advanced vehicle (bus) monitoring and communication. The system tracks vehicles in real-time and provides communications between vehicles and the dispatcher. Using average operating cost data (an average system cost of $ 8000 per vehicle), the report suggested that a 0.7% reduction in bus miles and a 1.6% reduction in fleet size would justify the investment.

2.3 Cost effective analyses of electric toll collection systems

Sisson[30] examined the benefits resulting from implementation of electronic toll collection in the Chicago area in terms of air pollution reductions. The assessment approach was primarily cost effective analyses, comparing the cost (in dollars per kilogram of pollutant removed by the system) with other alternatives.

2.4 Cost effective analyses of ATMS evaluation and guidelines

Intelligent Vehicle Highway System (IVHS) of America[31] produced guidelines for advanced traffic management systems (ATMS) assessments. Six broad categories of benefit were identified with each accompanied by a range of measures of effectiveness (Table 1). Some of the measures are those one would expect to find in a conventional cost-benefit analysis of a road infrastructure project, e.g., time savings and operation cost savings. Some are measurable but difficult to monetize, e.g., reduction in noise/air pollution. Others are difficult even to measure, e.g., driver stress and fatigue.

Table 1 IVHS benefit categories and measures of effectiveness[31]

Benefit	Measures of effectiveness
Increased capacity and operational efficiency	Throughput Balance of corridor volumes Travel speed Travel time Delay time Number of stops Incident detection time Delay at intermodal transfer point Vehicle occupancy Predictability of travel time
Improved safety	Number of accidents Number of secondary accidents Incident response time Driver fatigue
Reduced environmental and energy impacts	Fuel efficiency Fuel consumption Vehicle emission Noise pollution Right-of-way requirements
Increased productivity for motor carriers and service providers (tax, couriers, etc.)	Operating costs Volume of goods moved over existing facilities Working conditions for drivers 'Just-in-time' delivery
Increased comfort and convenience of travel	Motorist stress Motorist confusion Driver fatigue Predictability of travel time
Improved cooperation between transportation systems operators	Incident/congestion information Sharing of information Information gathering costs Consultation on implementation of control strategies

A 'utility-cost analysis' was suggested to consider the less tangible benefits of ATMS. This analysis is a subjective approach based on the value judgements of the agency undertaking the evaluation with the following steps:

(1) Define the primary goals or objectives to be achieved.

(2) Rank these goals on a numerical scale according to their relative importance (goal weighting).

(3) Identify the key feature or function for each goal (utility measures).

(4) Rank 'utility measures' and distribute 'goal weights' between them according to their 'relative importance'. (Thus, each 'utility measure' is assigned a number called utility points, which indicates its relative value.)

(5) Score the relevancy of each 'utility measure' to the considered system, with 0 for 'missing' and 5 for 'fully met' (relevancy score).

(6) Calculate the utility for each measure by multiplying the utility points (Step 4) with the relevancy score (Step 5).

(7) Get the total utility score by adding the utility across all the measures.

(8) Get the result, utility per dollar, by dividing the total utility score with the total system cost.

2.5 Evaluation through user willingness to pay

'User willingness to pay' was often used to evaluate ITS impacts on operation, safety, and the possibility of network benefits. In London, a 'Countdown' real-time information system for bus passengers was evaluated using the 'user willingness to pay' indicated on passenger surveys[32]. The survey results revealed that passengers were willing to pay an additional amount of around 53% of the average fare for use of the facility. The authors recognized that this appeared to be a high value and went to great lengths to check and validate their result. The cost of implementing the 'Countdown' system across the London network was estimated to add only 1 to 2 pence to the cost of an average passenger journey.

3 Socio-Economic Assessment for Convoy Driving

A UK EPSRC/LINK sponsored project named 'TACO' (technologies for advanced co-operative driving)[33] has been completed recently. The TACO project evaluated the impacts of convoy driving on motorway traffic by a simulation study with the FLOWSIM model[34]. A follow-up project[35] provided a more general assessment on the socio-economic impacts of convoy driving.

3.1 Identification of indicators

In the TACO project[36], convoy-equipped vehicles were assumed to have a 60-GHz spread spectrum radio, which enables the equipped vehicle to communicate with vehicles in the front and rear as well as in adjacent lanes when the vehicle is about to change lane or speed. Convoys are assumed to operate only in a reserved lane in the motorway, i.e., the convoy lane. Only convoy equipped vehicles can use this lane. Convoy operations in the convoy lane are considered to be fully automatic.

Convoys are expected to: (1) increase safety, (2) improve motorway driving comfort, (3) reduce environmental impacts and energy consumption, (4) increase motorway capacity, and (5) reduce journey time. However, the only indicators used for the socio-economic assessment were the 'reduction in journey time' and the 'increase in flow stability' as defined below.

Reduction in journey time The benefit of convoy driving on the journey time was defined as the time saving compared to the time without convoy driving. Convoy driving saves journey time for traffic in the convoy lane and for all traffic when the percentage of traffic in convoys is higher than 30% of the total motorway traffic. The benefits of journey time savings increase with the percentage of traffic in convoy driving[37]. 'Reduction in journey time' was selected because it shows the direct benefit to road users and extended benefits to the environment and it may be expressed in monetary terms.

Increase in flow stability The benefit of convoy operation on flow stability was defined as the reduction of the standard deviation (SD) of speed compared to the nonconvoy situation. A high SD of speed normally indicates frequent flow breakdowns, which reduce driving comfort, increase potential accidents, energy consumption, and environmental impact. The TACO project[38] showed that the benefit of convoy operation on the SD of speed is very significant for all traffic, particularly those in the convoy lane.

Convoy driving in a motorway is usually considered in the context of automated highway systems. The concept of convoys discussed in this paper differs from the more usual automated highway systems, as convoys do not rely on roadside support systems. In the TACO project[39], convoy-equipped vehicles communicate with all such vehicles around them. The potential costs to operate such a convoy driving system will include: infrastructure construction costs, system operation and enforcement costs, in-vehicle equipment purchase costs, and in-vehicle equipment operation/maintenance costs.

3.2 Methodologies

Two different socio-economic assessment methods, cost-benefit analyses and data envelopment analyses, were used to evaluate the convoy driving system. In the cost-benefit analyses, only the 'reduction in journey time' was considered as the sole system benefit, because both benefits and costs could be satisfactorily evaluated in monetary terms. The indicator, 'increase in flow stability', is difficult to value in monetary terms. The data envelopment analyses considered output indicators, 'reduction in journey time', and 'increase in flow stability'. The framework for the socio-economic impact assessment of convoy driving is shown in Fig. 1.

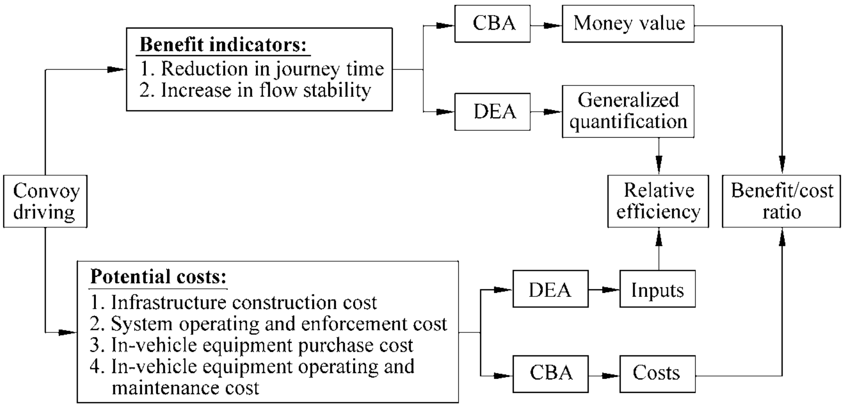

Fig. 1 Framework for socio-economic impact assessment of convoy driving

3.3 Cost-benefit analyses of convoy driving

3.3.1 Benefits of convoy driving

Benefits of time saving The monetary value of the time savings of convoy driving compared to that without convoys can be calculated by Eq. (1).

$$\text{BTS} = \text{Demand} \times \frac{\text{TS}}{3600 \times 5} \times 7.84 \times 1.9316 \tag{1}$$

where BTS is benefits of time savings (￡/(km • h)), TS is time savings for 5 km drive (s), 7.84 is time savings considering average vehicle occupancy (￡/vehicle-h[40]). The time saving benefits are listed in Table 2 in terms of the cost per km per hour.

Table 2 Convoy driving benefit estimates (￡/(km • h))

Demand level (vehicles • h)	Benefits of time savings			Benefits of operating cost savings			Benefits of reduced emissions		
	20% convoy	35% convoy	50% convoy	20% convoy	35% convoy	50% convoy	20% convoy	35% convoy	50% convoy
5500	–238.8	9.3	23.1	67.8	4.3	11.3	–0.4	0.0	0.0
6000	–491.7	76.2	98.9	59.0	28.1	38.5	–0.9	0.1	0.2
6500	–754.7	136.7	262.5	14.3	29.5	75.1	–1.3	0.2	0.5
7000	–1071.8	200.2	530.0	–49.1	15.1	95.4	–1.9	0.4	0.9

The valuation model for the personal (driver and passengers) time savings is derived from COBA, a UK government recommended program for appraisal of trunk road schemes in England, Wales, and Northern Ireland. COBA compares the costs of providing road schemes with the benefits derived by road users (in terms of time, vehicle operating costs, etc.) and expresses the results in terms of a monetary valuation[40]. To simplify the model, this study assumed an 'average vehicle' occupancy based on the traffic composition (car, other goods vehicle (OGV), and public service vehicle (PSV)). The assumption holds since this study assumes the same traffic proportions in the convoy operation simulation as in COBA[40]. This study also assumes that the proportion of working-time vehicle type and non-working-time vehicle type is the same in the convoy operation as in COBA. The annual average value of time per average vehicle is ￡7.84/vehicle-h (1994 values and prices). A factor of 1.9316 allowed for the inflation rate of 1.5% per year with the factor of 7.84 used to consider the value of time growth in line with the GDP per head[40] from 1994 to 2010.

Savings on vehicle operating costs The vehicle operating cost savings is a function of the travel speed. In the COBA model, the perceived fuel cost is estimated using Eq. (2), the non-fuel elements of the marginal perceived cost estimated using Eq. (3), and the total cost is then estimated using Eq. (4).

$$C_1 = (a + b/V + cV^2)(1 + mH + nH^n) \tag{2}$$

$$C_2 = a_1 + b_1/V \tag{3}$$

$$C = C_1 + C_2 \tag{4}$$

where C is the cost in pence per kilometer per vehicle, V is average link speed or the average speed in the convoy (km/h), H is the average link hilliness (m/km) which in these convoy simulations was zero, and a, b, a_1, b_1, c, m, and n are parameters defined for each vehicle category (car, OGV, and PSV). The parameter values are given in the COBA[40]. In the model, the proportions of car, OGV and PSV are assumed to be 0.85, 0.14, and 0.01, with the proportions of working and non-working cars as 0.854 and 0.146 in the convoy simulation. The 'average vehicle' operating costs are

$$C_{\text{agv}} = (0.85 \times C_{\text{car}} + 0.14 \times C_{\text{OGV}} + 0.01 \times C_{\text{PSV}})/100 \tag{5}$$

$$C_{\text{car}} = 0.854 \times C_{\text{non-working}} + 0.146 \times C_{\text{working}} \tag{6}$$

C_{car} is defined as the working and non-working car perceived cost (pence per kilometre per vehicle); C_{OGV} and C_{PSV} are the working perceived costs for the other goods vehicles and public service vehicles (pence/(km • vehicle)).

The benefits for operating cost savings (BOCS, ￡/(km • h)) are:

$$\text{BOCS} = \text{Demand} \times (C_{\text{avg-non-convoy}} - C_{\text{avg-convoy}}) \times 1.7554 \tag{7}$$

where $C_{\text{avg-non-convoy}}$ is the nonconvoy operating cost (£/(km • average vehicle)), $C_{\text{avg-convoy}}$ is the convoy operating cost (£/(km • average vehicle)), and 1.7554 is a factor to reflect the annual compounded change in the fuel prices (including an inflation ratio of 1.5% per year).

The savings for the vehicle operating costs are listed in Table 2 in monetary terms. At lower demand levels, the convoy operating characteristics cause the vehicle travel speed to be sensitive to the convoy percentage. Since operating costs are closely related to vehicle travel speed (Eq. (2)), the operating cost savings are also sensitive to the convoy percentage. This result is seen in Table 2 where the operating cost saving decreases as the convoy percentage increases from 20% to 35% and then increases as the convoy percentage increases from 35% to 50% for the demand levels of 5500 and 6000 vehicles/h.

Emission reduction due to journey time reduction There is no appropriate methodology to accurately estimate the full cost of emissions. However, the analysis of the costs and benefits would not be complete without consideration of the pollution impact. To simplify the model, the methods used in the TRL report[41] were used to analyze the benefits of the emission reduction. The cost associated with pollutants is the direct public costs of treatment of pollution related illnesses, e.g., hospitalization costs. These do not include the wider social and economic costs of the consequences of these illnesses. These indirect costs are likely to be much greater, but cannot at present be adequately measured. The pollution cost estimate should, therefore, be taken as indicative of the impact, but do not necessarily reflect the full economic and social costs. The emission volumes and the valuations of pollutants found in the TRL report[41] were used without consideration of changes of the pollution treatment costs since the report was published. The emissions volume per vehicle is based on the 'average vehicle' category. The benefits of the reduced emissions due to reduced journey times (BRE, £/(km • h)) is given by

$$\text{BRE} = \text{Demand} \times \frac{\text{TS}}{3600 \times 5} \times 0.0268 \qquad (8)$$

where 0.0268 is the cost of the emission pollutants in pounds per vehicle-hour-delay and TS is the time savings for 5 km drive (s). The estimated benefits are listed in Table 2.

3.3.2 Evaluation of convoy driving costs

Although convoy driving does not rely on roadside support systems (e.g., beacons), it still has infrastructure and operating costs which include traffic management centre construction costs, traffic management centre operating costs, user investment costs, and the in-vehicle equipment operating costs.

A common telematics infrastructure has been considered for the advanced transport telematics in the UK[41] with the capital cost of the centralized architecture estimated to be £372.68 million and the total operating cost of the centralized architecture as £193.74 million/y for 51 272 km of road (motorway and category A roads). These costs were used as the basis for the following estimates.

Traffic management centre construction costs Since the average capital cost is 372 680 000/ 51 272 = 7269 (£/km) for two-way traffic per kilometre, for one way convoy operation, the average capital cost would be 372 680 000/51 272/2=3634 (£/km). Considering the rapid price reductions for telematics infrastructure products, the average capital cost was not adjusted to account for inflation.

Traffic management centre operating costs The average annual operating cost is 193 740 000/ 51 272=3779 (£/km) for two-way traffic. Then the average annual operating cost is 193 740 000/51 272/2= 1889(£/(km • y)) for the one-way traffic in the simulations. Again considering the price reductions for telematics infrastructure products, the average annual operating cost was not adjusted.

User investment costs for in-vehicle equipment The equipment cost is about £300/vehicle[41], which was not adjusted for inflation.

Operating costs of in-vehicle equipment The operating cost is about £50/(vehicle • y)[41]. This cost was multiplied by 1.2318 for an inflation ratio of 1.5% per year from 1996 to 2010 to give a current in-vehicle equipment operating cost of £62/(vehicle • y).

3.3.3 Benefit-cost ratios for convoy driving

The benefits of convoy driving in terms of monetary savings are based only on the journey time savings. Using the benefits and cost analysis in the previous section, the total benefits for the convoy driving (PVB, 10^4 £) is

$$\mathrm{PVB} = (\mathrm{BTS} + \mathrm{BOCS} + \mathrm{BRE}) \times 8 \times 365 \times 10^{-4} \times \frac{1 - 1.015^{10} \times 1.06^{-10}}{0.06 - 0.015} \tag{9}$$

where PVB is the benefit for a 10-year cycle life assuming that the convoy system operates 8 h/d. The discount rate is assumed to be 6% per year and the inflation ratio is 1.5% per year from 2010 to 2020.

The incremental costs of convoy driving include the average capital cost of ￡3634/km, the average annual operation cost of ￡1889/(km • y), the user investment cost for in-vehicle equipment of ￡300/vehicle and the operating costs of the in-vehicle equipment of ￡62/(vehicle • y). The total present value of the costs (PVC) is:

$$\begin{aligned}\mathrm{PVC} = ((&3634 + 300 \times \mathrm{Demand} \times \\ &\mathrm{percentage\_of\_convoys} / 0.7) + \\ &(1889 + 62 \times \mathrm{Demand} \times \\ &\mathrm{percentage\_of\_convoys} / 0.7) \times \\ &\frac{1 - 1.015^{10} \times 1.06^{-10}}{0.06 - 0.015} \times 10^{-4}\end{aligned} \tag{10}$$

where PVC has units of 10^4 ￡.

The net present value (NPV) and benefit-cost ratio (BCR) are

$$\mathrm{NPV} = \mathrm{PVB} - \mathrm{PVC} \tag{11}$$

$$\mathrm{BCR} = \frac{\mathrm{PVB}}{\mathrm{PVC}} \tag{12}$$

The benefit-cost ratio shown in Fig. 2 and Table 3 show no positive NPV when the percentage of convoys is ≤20% and the demand is below 6000 vehicles/h. The convoy systems have a good benefit-cost ratio (>1) when the percentage of convoy vehicles is above 35% and the demand is greater than 6000 vehicles/h.

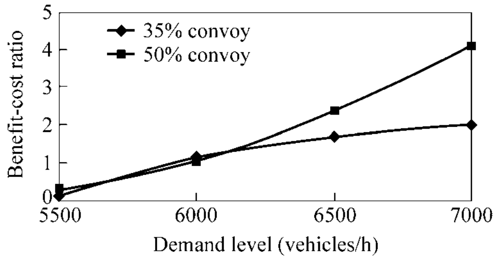

Fig. 2 Benefit-cost ratio for convoy driving

Table 3 Convoy cost-benefit analysis

Demand level (vehicles/h)	20% convoy			35% convoy			50% convoy			Benefit-cost ratio	
	PVB (10^4￡)	PVC (10^4￡)	NPV (10^4￡)	PVB (10^4￡)	PVC (10^4￡)	NPV (10^4￡)	PVB (10^4￡)	PVC (10^4￡)	NPV (10^4￡)	35% convoy	50% convoy
5500	–391.5	102.1	–493.7	31.0	191.9	–160.9	78.8	273.7	–194.9	0.16	0.29
6000	–990.1	111.2	–1101	238.7	209.2	29.5	314.3	298.4	16.0	1.14	1.05
6500	–1694	120.3	–1814	380.2	226.4	153.8	772.2	323.0	449.1	1.68	2.39
7000	–2564	129.5	–2694	492.6	243.7	248.9	1430.5	347.7	1082.7	2.02	4.12

3.4 Data envelopment analyses for convoy driving evaluation

The data envelopment analysis method for evaluating the socio-economic impacts of convoy driving defines each scenario as a decision making unit as shown in Table 4.

Output indicators considered for the data envelopment analysis include the total journey time savings, Y_1, and the total flow stability gain, Y_2. The input indicators include the traffic management centre construction costs, traffic management centre operating/enforcement costs, and user costs for purchasing, operating, and maintaining in-vehicle equipment. Assuming a 10-year life cycle, the costs for traffic management centre construction, operating and enforcement, X_1, are

$$X_1 = (3634 \times \frac{0.06 \times (1 + 0.06)^{10}}{(1 + 0.06)^{10} - 1} + 1889) \times 10^{-4}\ (10^4\ ￡/\mathrm{y}).$$

The in-vehicles equipment purchasing, operating and maintaining costs, X_2, are

$$X_2 = \mathrm{Demand} \times \mathrm{percent\_in\_convoys} / 0.7 \times (300 \times \frac{0.06 \times (1 + 0.06)^{10}}{(1 + 0.06)^{10} - 1} + 50) \times 10^{-4}\ \ (10^4\ ￡/\mathrm{y}).$$

The input and output indicators and the data envelopment analysis results are listed in Table 4.

As shown in Table 4, the journey time savings are negative for scenarios DMU1, DMU2, DMU3, and DMU4; therefore, the data envelopment analysis (DEA)

Table 4 Input and output indicators and evaluation results from the data envelopment analysis

DMU	Convoy (%)	Demand level (vehicles/h)	$\frac{X_1}{10^4 \text{£} \cdot \text{y}^{-1}}$	$\frac{X_2}{10^4 \text{£} \cdot \text{y}^{-1}}$	Y_1	Y_2	h value for Y_1 and Y_2	h value for Y_1 only	BCR	Relative BCR
1	20	5500	0.2353	13.88	−5.68	−1.5				
2		6000	0.2353	15.15	−11.69	1.1				
3		6500	0.2353	16.41	−17.94	2.2				
4		7000	0.2383	17.67	−25.48	3.8				
5	35	5500	0.2353	24.30	0.22	2.4	0.456	0.032	0.16	0.039
6		6000	0.2353	26.51	1.81	3.3	0.575	0.239	1.14	0.277
7		6500	0.2353	28.72	3.25	3.9	0.629	0.397	1.68	0.408
8		7000	0.2353	30.92	4.76	6.7	1.000	0.540	2.02	0.491
9	50	5500	0.2353	34.71	0.55	3.9	0.522	0.056	0.29	0.070
10		6000	0.2353	37.87	2.35	5.3	0.653	0.218	1.05	0.256
11		6500	0.2353	41.02	6.24	6.3	0.719	0.533	2.39	0.581
12		7000	0.2353	44.18	12.60	9.4	1.000	1.000	4.12	1.000

was not completed. For scenarios DMU5 to DMU12, the relative efficiencies h corresponding to indicators Y_1 and Y_2 and that corresponding to just Y_1 are listed in Table 4 which shows that for a demand of 7000 vehicles/h, both 50% and 35% convoy scenarios are DEA efficient when both the journey time savings and the flow stability increase are included in the model. For a fixed percentage of convoys, increased demand levels increase the efficiency h. The 50% convoy scenario with a demand of 7000 vehicles/h is efficient with only the journey time saving Y_1 considered in the model. The results in Table 4 verify that when both Y_1 and Y_2 are included in the analysis, the efficiency is greater than when only Y_1 is included. The results indicate how excluding an output indicator in a data envelopment analysis may result in underestimation of the efficiency. For example, the previous cost-benefit analysis which did not include the benefits of flow stability produced by convoys in monetary units underestimated the benefits of convoy driving.

The relative efficiencies from the data envelopment analysis agree well with the relative values of the benefit-cost ratios ($\text{BCR}/\text{BCR}_{\text{max}}$), as shown in Table 4, because in the data envelopment analysis model, the ratios of weights[26] to the inputs (negative indicators) and outputs (positive indicators) are equal to the ratio of the shadow prices for the inputs and outputs. Therefore, the data envelopment analysis method can be used to evaluate the impacts that are difficult to decide in monetary units.

4 Conclusions

While cost-benefit analyses remain the dominant advanced transport telematics evaluation method, cost effective analyses and various multi-criteria appraisals (e.g., data envelopment analysis) are very useful when benefits are difficult to measure or evaluate in monetary terms. Cost effective analyses and multi-criteria appraisal approaches have been widely used to define and prioritise objectives and provide useful evaluation of the most promising broad policy areas.

Both cost-benefit analyses and data envelopment analysis have been applied in this study for socio-economic impact assessments of convoy driving. The cost-benefit analyses show that convoy systems can have worthwhile benefit-cost ratios (BCR>1) when the percent of convoy traffic is above 30% and with a traffic demand greater than 5500 vehicles/h for a three-lane motorway. The data envelopment analysis assessment results show that for a fixed percentage of convoy driving, increased demand increases the data envelopment analysis relative efficiency, h. The results also indicate that the losing of some output indicators may lead to underestimates of the efficiency of an ITS. The data envelopment analysis method may be useful for appraisal of transport systems containing indicators which are difficult to evaluate in monetary terms.

Existing socio-economic evaluation procedures are not directly suitable for either measuring or evaluating many impacts of ITS, so substantial efforts are needed to develop ITS project appraisals having the same form, level of sophistication and consistency as appraisals of conventional transport infrastructure investments.

In addition, since estimates of benefit and cost indicators of an ITS are very difficult to evaluate, further research is needed to develop better assessments of the socio-economic impact of ITS.

References

[1] Polk A E. What ITS has to offer municipal governments. In: 7th World Congress on Intelligent Transport Systems, Paper number 1051. Turin, Italy, 2006.

[2] Clowes D J. National ITS including transportation information highways (TIH), National Control Centres and RTA. In: 7th World Congress on Intelligent Transport Systems, Paper number 5001. Turin, Italy, 2000.

[3] Kikuchi H, Kawasaki S, Nakazato G. ITS in Japan: Current status and future directions. In: 7th World Congress on Intelligent Transport Systems, Paper number 3149. Turin, Italy, 2000.

[4] Department of the Environment. Transport and the Regions of the UK. Guidance on the New Approach to Appraisal, University of Southampton, 1998.

[5] Polk A E. The ITS benefits special studies effort at the US DOT. In: 7th World Congress on Intelligent Transport Systems, Paper number 1050. Turin, Italy, 2000.

[6] McDonald M, Wu J, Juan Z. The socio-economic impacts assessment for motorway advanced transport telematics system: Final report to the engineering and physical sciences research council. Transportation Research Group, University of Southampton, 2001.

[7] McDonald M, Wu J, Brackstone M. TACO (Technologies for Advanced Co-operative Driving) final report to the engineering and physical sciences research council. Transportation Research Group, University of Southampton, 1998.

[8] Zhang X, Kopener P, Sexton B, Maltby D, Morello S. Guidebook for Assessment of Transport Telematics Applications, Deliverable DVQ5.1 Version 2.0, CONVERGE Project TR 1101, 1996.

[9] Bristow L, Pearman A, Shires J. An assessment of advanced transport telematics evaluation procedures. *Transport Reviews*, 1997, **17**(3): 177-205.

[10] Ran B, Lee K Y K, Dong H. Cost-benefit analysis on deployment of automated highway systems. *Transportation Research Record*, 1997, **1588**: 137-144.

[11] Baum H, Geissler T. Assessing socio costs and socio benefits of AHS: Methodological and empirical approach for the introduction of CHAUFFEUR in Germany and Japan. In: 7th World Congress on Intelligent Transport Systems, Paper number 2224. Turin, Italy, 2000.

[12] Baum H, Schulz W H, Geissler T. Efficiency analysis of automated highway systems implementation strategies for Japan. Cologne University, Germany, 1999.

[13] Schnarr T J, Kitaska K. Evaluating ATMS from a business respective: Vancouver's traffic management program. In: Third World Congress on Intelligent Transport Systems. Orlando, Florida, 1996: 249-250.

[14] Shibata M. The economic effect of in-car navigation system. In: Proceedings of IEEE 3rd Vehicle Navigation and Information Systems Conference. Oslo, Norway, 1992: 632-637.

[15] Motyka V, James B. Concrete application of road information strategy. VMS in ILE-DE-FRANCE. Detailed quantitative evaluation and first glimpse of socio-economic benefits. In: Proceedings of the 1st World Congress on Applications of Transport Telematics and Intelligent Vehicle-Highway Systems. Paris, 1994, **3**: 1364-1371.

[16] Tarry S, Graham A. The role of valuation in ATT development (Part 4): Evaluation of ATT systems. *Traffic Engineering & Control*, 1995, **36**(12): 688-693.

[17] Jeffery D. The potential benefits of route guidance. TRRL Laboratory Report LR 997. Crowthorne, Berkshire, 1981.

[18] Harvey S. The political and economic implications of ATT: Towards an intelligent transport system. In: Proceedings of the 1st World Congress on Applications of Transport Telematics and Intelligent Vehicle-Highway Systems, Paris, 1994, **6**: 3125-3132.

[19] Lee D B Jr. Benefit-cost evaluation of traveller information: Seattle's Washington State Department of Transportation website. *Transportation Research Record*, 2000, **1739**: 25-34.

[20] Charnes A, Cooper W W, Huang Z M, Sun D B. Polyhedral cone-ratio DEA models with an illustrative application to large commercial banks. *Journal of Econometrics*, 1978, **46**(1/2): 73-91.

[21] Walters L C, Thurgood G, Adolphson D L. New approach to integrating engineering, managerial, and political judgment: Development of the Utah project prioritisation system. *Transportation Research Record,*1993, **1400**: 1-9.

[22] Minken H, Odeck J. Applying data envelopment analysis (DEA) to project selection: Transportation planning methods. In: Proceedings of Seminar D, PTRC European

Transport Forum. Brunei University, England, 1996.

[23] Kerstens K. Technical efficiency measurement and explanation of French urban transit company. *Transportation Research, Part A*, 1996, **30A**(6): 431-452.

[24] Viton P A. Changes in multi-mode bus transit efficiency, 1988-1992. *Transportation*, 1998, **25**(1): 1-21.

[25] Parker D. The performance of BAA before and after privatisation: A DEA study. *Journal of Transport Economics and Policy*, 1999, **33**(2): 133-146.

[26] Juan Z, Wang J, Jing J. DEA and the effectiveness of technical scales of transport enterprises. *Science and Technology of Highway and Transport*, 1994, **11**(4): 44-50. (in Chinese)

[27] Taylor S T, Singleton B N. ITS: Communications technology case study. *ITE Journal*, 1996, **66**(5): 28.

[28] De Corla-Souza, Patric Culp M, Hunt J, Cohen H, Haling D. A new tool for benefit-cost analysis in evaluating transport alternatives. In: The Sixth TRB Conference on the Application of Transportation Planning Methods. Dearborn, Michigan, USA, 1997: 11.

[29] Daetz D, Bebendorf M. A socio-economic impact assessment of the Los Angeles automatic vehicle monitoring (AVM) demonstration. Report by SYSTAN Incorporated, Urban Mass Transportation Administration, Washington, DC, 20590, USA, 1982: 108.

[30] Sisson M. Air quality benefits of electronic toll collection. *Transportation Quarterly*, 1995, **49**(4): 93-101.

[31] IVHS America. Guidelines for an ATMS. Washington, DC, 20036-1993, USA, 1992: 100.

[32] Smith R. London transports buses: ATT in action and the London countdown route 18 report. In: Proceedings of the 1st World Congress on Applications of Transport Telematics and Intelligent Vehicle-Highway Systems. Paris, 1994, **6**: 3048-3055.

[33] Couch N R, Brackstone M, Wu J, McDonald M, Landsdown T. Technologies for advanced co-operative driving. Final Project Report to EPSRC/LINK, 1999.

[34] Wu J, Brackstone M, McDonald M. Fuzzy sets and systems for a motorway microscopic simulation model. *International Journal of Fuzzy Sets and Systems*, 2000, **116**(1): 65-76.

[35] McDonald M, Mareden G, Brackstone M. Deployment of interurban ATT test scenarios (DIATS): Implications for the European road network. *Transport Review*, 2001, **21**(3): 303-336.

[36] Wu J, McDonald M, Brackstone M**.** Effect of convoy driving on motorway flow stability and capacity. In: Proceedings of the 10th International Conference on Road Transport Information and Control. IEEE. London, 2000: 91-95.

[37] Wu J, McDonald M, Brackstone M. TACO project simulation results (Part two): The impacts of convoy operations on journey time. Department of Civil and Environmental Engineering, University of Southampton, 1999.

[38] Wu J, McDonald M, Brackstone M. TACO project simulation results (Part three): The impacts of convoy operations on flow stability. Department of Civil and Environmental Engineering, University of Southampton, 1999.

[39] Wu J, McDonald M, Brackstone M. TACO project simulation results (Part one): Motorway capacity with convoy operation. Department of Civil and Environmental Engineering, University of Southampton, 1999.

[40] Department of the Environment. Transport and the Regions of the UK. The COBA Manual, 1997.

[41] Transport Research Laboratory. Review of the potential benefits of road transport telematics. TRL, Crowthorne, UK, 1996.