TOPIC 9
ADVANCED TRAVELLER
INFORMATION SYSTEMS

# NETWORK EFFICIENCY AND DRIVERS' BEHAVIOUR IN AN ATIS ENVIRONMENT

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**Abstract**

This paper analyses the welfare impacts of providing different types of information to a group of potential road users. Two groups of drivers are considered: informed and uninformed ones, and three kinds of information are dealt with: perfect, imperfect, and no information. An equilibrium model is used for obtaining insight into the impacts of information on efficiency and equity.

## INTRODUCTION

Congestion is severely affecting most metropolitan areas around the world. Numerous instruments to tackle congestion have been studied in the past. One may, for instance, think of instruments such as electronic road pricing, fuel taxation, regulatory parking policies, an improvement of public transport by higher subsidies, etc. Another instrument, widely viewed to be able to relieve part of the congestion problem is the use of new information technologies in transport networks, witness for instance the DRIVE I and II programmes of the European Community and the Intelligent Vehicle Highway Systems (IVHS) efforts in the United States. Information provision to drivers is believed to improve the drivers' knowledge of the traffic situation on the roads and thus to improve drivers' decision-making (Ben-Akiva et al. 1991; Bonsall 1992). Unfortunately, the real picture of the effects of information provision to drivers is more clouded than the intuitive reasoning above suggests. Information provision is believed to improve drivers' individual decision-making. At an aggregate level this might imply that information might direct traffic flows to the user equilibrium (Emmerink et al. 1993b; Wardrop 1952), ie a situation characterized by driver optimal decisions. However, the inequality between Wardrop's first (user equilibrium) and second principle (system optimum) in congested situations (Sheffy 1985) indicates that information provided to drivers will not direct the traffic flows towards the system optimum, ie the most effective use of the transport network. This observation leaves the interesting (and still open) question to which extent information is able to improve network efficiency, and hence to partly diminish the external costs caused by traffic congestion.

In the literature, sparse attention has been paid to answering this question. Most papers use either a simulation approach to infer conclusions on network efficiency (El Sanhouri 1994; Emmerink et al. 1993a, 1994a, Mahmassani and Jayakrishnan 1991) or an empirical analysis in which the impacts of information on drivers' individual behaviour is studied (Caplice and Mahmassani 1992, Conquest et al. 1993, Emmerink et al. 1994c, Mannering et al. 1994, Spyridakis et al. 1991, Van Berkum and Van Der Mede 1993). One of the few theoretical "economic" papers on information provision is the one by Emmerink et al. (1994b) in which a qualitative economic analysis is conducted. Another attempt in this direction has recently been carried out by Verhoef et al. (1994a) in which the welfare improving properties of pricing and information provision, conducted in isolation as well as in combination, were analysed.

The objective of the current paper is to enhance our insight into the welfare economic effects of information provision to a group of drivers, ie to gain more insight into the mechanisms affecting the impact of providing information. We will do so by theoretically analysing the impact of information provision on network efficiency. In addition, we will consider the equity aspects of information provision by answering questions such as "who benefits (or disbenefits) most from information?" and "do uninformed drivers also benefit?". To study these questions, we will confine ourselves to the economic fundamentals of information provision, and therefore limit the analysis to using simple economic equilibrium models rather than complex equilibrium assignment models.

The model presented here is a static economic equilibrium model. An elastic demand curve is used to model demand for mobility, while an increasing cost curve represents the costs for travel (including congestion costs). In particular, the elastic demand curve feature of our model distinguishes our approach from the existing literature on information provision. The equilibrium models reported on in the literature, generally assume that demand is fixed (inelastic), see for example Al-Deek and Kanafani (1993), Arnott et al. (1990, 1991, 1992, 1994), and Tsuji et al. (1985). However, the assumption of inelastic demand is a severe limitation of the analysis of information provision, because changes in usage due to changes in costs are completely ignored. In a recent paper, Arnott et al. (1993) presented an elastic demand version of Vickrey's (1969) model of peak-hour bottleneck congestion. The current paper is complementary to their work since it adds (1) information provision to drivers, and (2) stochasticity in terms of link travel costs and demand for mobility.

The paper is organised in the following manner. In the next section, the model is presented, while in following section its properties are analysed. The final section contains some concluding comments and future research directions.

## ONE-LINK EQUILIBRIUM MODEL WITH SHOCKS ON THE COST SIDE

In this section, the model will be presented in its simplest form. In this form, the network is limited to one link only. Clearly, in such a simple network potential beneficial route split effects of information provision cannot be analysed, ie beneficial effects of information provision owing to the fact that informed drivers change route in circumstances of incidents (see Emmerink et al. (1995) for a simultaneous consideration of route split and modal split in relation to information). Mode split effects however, can be addressed in the current context and these are precisely the ones that have widely been ignored in the literature thus far, due to the underlying assumption in most models that demand is inelastic. In such models all (fixed) demand is assigned to the network without allowing for changes in mode split.

The current section is structured as follows. The next sub-section presents the model with perfect information and informed and uninformed drivers. To assess the impacts of information provision this model is compared with the model described in the subsequent sub-section in which no information is available. To acknowledge that any real-world motorist information system is likely unable to supply perfect information we present a model in which imperfect information is provided to informed drivers in final sub-section.

### Perfect information

In the model, the demand side is modelled using two groups of drivers, ie those who are provided with information and those who are not. The demand function for informed drivers is denoted by $D_i$, and for uninformed drivers by $D_u$. The supply side of the system is modelled using the well-known concept of link travel cost functions. It is assumed that the link travel cost function has either the functional form $C^0$ or $C^1$, depending on the state of the system. State 1 reflects *non-recurrent* congestion occurring with a probability p, while state 0 denotes *recurrent* congestion which occurs with a probability 1-p. The distinction between non-recurrent and recurrent congestion lies in the higher travel costs in the non-recurrent state, ie $C^1(x)>C^0(x)$ and $dC^1(x)/dx>dC^0(x)/dx$ for all x, where x denotes the number of drivers using the one-link network. This increase in travel (and congestion) costs is caused by random (unpredictable) incidents such as traffic accidents, lane closures, etc. In the current paper we confine ourselves to stochastic shocks in the link travel cost function. In Emmerink et al. (1994d) stochastic shocks in the demand functions have been analysed as well.

The above introduced random cost component in combination with the elastic demand functions render an analysis of the impacts of information provision relevant. In the model we will assume that uninformed drivers use the probability p to determine the *expected* cost function in the transport system, while informed drivers base their behaviour on the actually *prevailing* cost function. Hence, uninformed drivers are familiar with average traffic conditions, but are unaware of any day-specific traffic situation. In line with common economic theory, an uninformed road user will then only use the network when his/her private benefits are at least equal to, or exceed expected private costs. An informed road user will use the network if private benefits are at least equal to actual private costs for the prevailing state of the transport system. The equilibrium that is reached in this way conforms to Wardrop's first principle, the user equilibrium (Wardrop, 1952), as both may be characterized by individual maximizing behaviour.

Transferring the verbally explained equilibrium conditions into mathematical expressions yields the model given in expressions 1 to 1, where $N_{p,i}{}^0$ and $N_{p,i}{}^1$ denote the number of informed (i) drivers using the one-link network in state 0 and state 1, respectively, and $N_{p,u}$ the number of uninformed (u) drivers. Subscript p (referring to perfect information) denotes the equilibrium road usage values of the current model. Equations 1 and 2 ensure that the marginal informed driver, ie the informed driver who is indifferent between using the one-link network and an alternative (implying zero marginal net private benefits), equates private costs and private benefits for both state 0 and state 1. In a similar fashion expression 1 guarantees that the marginal uninformed driver experiences zero expected net private benefits. For the non-marginal drivers (expected) net private benefits are higher than zero, due to the downward sloping demand function. Finally, the additional condition that road usage is non-negative has to be imposed, ie $N_{p,i}^0$, $N_{p,i}^1$ and $N_{p,u}$ have to be greater than or equal to zero.

$$D_i(N^0_{p,i}) \le C^0(N^0_{p,i}+N_{p,u})\,,\ N^0_{p,i} \ge 0\ \ N_{p,i}^0 \bullet \left(D_i(N^0_{p,i}) - C^0(N^0_{p,i}+N_{p,u})\right)=0 \qquad (1)$$

In the analysis below, we will assume that the *group-regularity* condition applies for each group, ie for each state and each group of drivers the network will at least be marginally used. For a one-link network this is a plausible assumption, since it seems likely that for each state at least some uninformed and informed drivers will use the network. Imposing this restriction implies that model expressions 1 to 3 can be rewritten to equations 4 to 6.

$$D_i(N^1_{p,i}) \le C^1(N^1_{p,i}+N_{p,u})\,,\ N^1_{p,i} \ge 0\ \ N_{p,i}^1 \bullet \left(D_i(N^1_{p,i}) - C^1(N^1_{p,i}+N_{p,u})\right)=0 \qquad (2)$$

$$\begin{gathered} D_u(N_{p,u}) \le (1-p)\bullet C^0(N^0_{p,i}+N_{p,u}) + p\bullet C^1(N^1_{p,i}+N_{p,u})\,,\ N_{p,u} \ge 0 \\ N_{p,u}\bullet\left(D_u(N_{p,u}) - \left((1-p)\bullet C^0(N^0_{p,i}+N_{p,u}) + p\bullet C^1(N_{p,i}^1+N_{p,u})\right)\right)=0 \end{gathered} \qquad (3)$$

$$D_i(N^0_{p,i}) = C^0(N^0_{p,i}+N_{p,u}) \qquad (4)$$

$$D_i(N^1_{p,i}) = C^1(N^1_{p,i}+N_{p,u}) \qquad (5)$$

$$D_u(N_{p,u}) = (1-p)\bullet C^0(N^0_{p,i}+N_{p,u}) + p\bullet C^1(N^1_{p,i}+N_{p,u}) \qquad (6)$$

Figure 1 gives a diagrammatic representation for the situation where $C^j(x)$ (j=0,1) is linear and, in addition, the slope of the cost functions are identical.

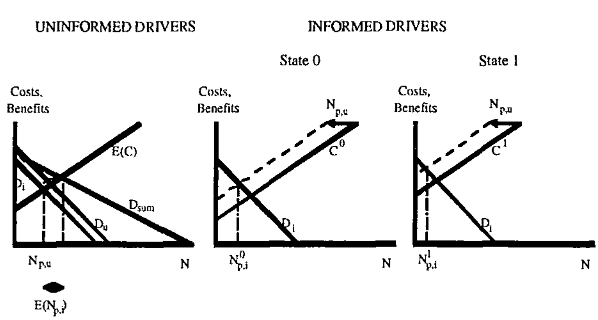


**Figure 1 Graphical illustration of equilibrium model with informed and uninformed individuals**

In the left panel of Figure 1, uninformed drivers equate expected link travel costs to their private benefits. In doing so, they take account of the effect that the expected number of informed drivers will have on their costs. Given the assumptions on the cost functions, the expected number of uninformed drivers can be found by equating their demand to expected user cost. This leads to a total number of $N_{p,u}$ uninformed individuals using the network. Next, informed drivers shift the prevailing cost curve $C_j$ (j=0,1) with an amount $N_{p,u}$ to the left (see the dashed cost curves in Figure 1) to account for travel demand of uninformed road users. Then for each state, the number of informed road users is found by equating demand with prevailing costs (as given by the dashed cost curve), leading to $N_{p,i}^0$ informed drivers using the network in state 0, and $N_{p,i}^1$ informed drivers in state 1. Under the assumptions, $N_{p,i}^1$ is smaller than $N_{p,i}^0$: when congestion is of the non-recurrent type, some informed drivers will not use the car, but the other transport mode (or remain at home).

It can easily be demonstrated that $N_{p,u}$, $N_{p,i}^0$ and $N_{p,i}^1$ are the only equilibrium values. In general, in user equilibrium models it can be shown that the equilibrium link travel flows are unique (Sheffy, 1985). Conversely, path travel flows are not unique. In our one-link network however, a path is equivalent to a link, and hence we witness the similarity between our result and the literature.

## No information

In order to assess the welfare economic impacts of information provision, it is useful to compare the economic system presented in expressions 1 to 3 with its performance in case no information is available to the informed drivers. It is straightforward to represent this model in equations 7 and 8.

$$\begin{aligned} &D_i(N_{n,i}) \leq (1-p)\bullet C^0(N_{n,i}+N_{n,u}) + p\bullet C^1(N_{n,i}+Nn,u)\,,\ N_{n,i}\geq 0 \\ &N_{n,i}\bullet\left(D_i(N_{n,i}) - ((1-p)\bullet C^0(N_{n,i}+N_{n,u}) + p\bullet C^1(N_{n,i}+N_{n,u}))\right)=0 \end{aligned} \tag{7}$$

The subscript n (referring to no information) is used to distinguish the equilibrium values of this model with the equilibrium values of the model described in the previous section. Expression 7 shows that the previously informed drivers now also base their costs on the *expected* link travel costs, rather than on the prevailing link travel costs. By imposing the group-regularity condition, as defined in the previous section, these expressions can be simplified to two equalities.

$$\begin{aligned} &D_u(N_{n,u}) \leq (1-p)\bullet C^0(N_{n,i}+N_{n,u}) + p\bullet C^1(N_{n,i}+Nn,u)\,,\ N_{n,u}\geq 0 \\ &N_{n,u}\bullet\left(D_u(N_{n,u}) - ((1-p)\bullet C^0(N_{n,i}+N_{n,u}) + p\bullet C^1(N_{n,i}+N_{n,u}))\right)=0 \end{aligned} \tag{8}$$

## Imperfect information

In the current section we will present an equilibrium model in which part of the drivers is uninformed and the other part imperfectly informed. By considering the case of imperfect information we acknowledge that any real-world motorist information system is likely unable to supply perfect information. Some sources affecting the quality of the information are (1) measurement errors; (2) delays in transmitting the information; (3) a discrete (rather than continuous) updating frequency; (4) the format in which the information is presented, etc. (see Emmerink et al. (1994a) and Watling and Van Vuren (1993) for more details). It is essential to understand in which direction and to what extent these kinds of (random) errors have an impact on the performance of the transport network.

In order to present the model in which drivers who have an interest in up-to-date information are supplied with imperfect information, we will first introduce the new concept of *substate*. A substate can be seen as an "information state", involving the provision of imperfect information, which enables the informed drivers to adopt the initial probabilities p (of having high travel costs) towards more likely levels $p_j$ in both substates. In the model below we will assume that there are two possible substates, denoted with 0 and 1, respectively. Substate 0 occurs with probability 1-q, while substate 1 takes place with probability q. In substate j (j=0,1), the link travel cost function $C^1$ prevails with probability $p_j$, while the link travel cost function $C^0$ is the relevant one with probability $1-p_j$. It will be assumed that the information system does not directly provide information on the prevailing state, but only on the substate. This allows informed users to make a better prediction of the actual state compared with the uninformed drivers.

Clearly, the following relationship between p (the probability that state 1 occurs), $p_j$ (the probability that state 1 occurs conditioned on the occurrence of substate j) and q (the probability that substate 1 occurs) should hold:

$$P(state\ 1) = p = p_0 \bullet (1-q) + p_1 \bullet q = \sum_{j=0}^{1} P(state\ 1 \mid substate\ j) \bullet P(substate\ j) \tag{9}$$

The left hand side of the above expression gives the probability that link travel cost function $C^1$ prevails, while the right-hand side denotes the same probability, but now calculated by conditioning on the occurrence of the substate concerned.

If the above expression representing unbiasedness of information provision, does not hold, then either informed or uninformed road users are basing their trip-making decisions on biased estimates of the traffic conditions. On economic grounds, an equilibrium founded on these assumptions cannot be viewed to represent a long-run stable situation. Moreover, in the literature on information provision in transport networks, it is regarded infeasible to deliberately supply faulty information, since it is impossible to consistently cheat (potential) road users. The empirical evidence in Bonsall and Parry (1991) and Bonsall and Joint (1991) suggests that drivers will not always follow the information that is provided by a motorist information system. Particularly, drivers that are familiar with the network are likely to ignore guidance that they do not perceive as being best for themselves, or which lacks credibility. As a consequence, the deliberate manipulation of drivers' decision-making to maximise system performance rather than individual benefits is unlikely to succeed in the long run.

In the model we assume that informed drivers know with certainty which substate is prevailing (they are provided with imperfect day-specific traffic conditions), and in addition, know the relevant probabilities $p_j$ (j=0,1), ie the probability that a certain state occurs conditioned on the occurrence of the substate j. As before, uninformed drivers are familiar with average traffic conditions, and therefore know the probabilities p, $p_j$ (j=0,1), and q, but are not aware of any day-specific traffic situation. Without loss of generality, we will assume that $p_0$ is smaller than or equal to $p_1$ indicating that there is a greater probability of high congestion when substate 1 occurs.

Since informed drivers are informed on the relevant substate, they will base their behaviour on the expected link travel costs given the occurrence of a substate, while uninformed drivers will simply base their behaviour on expected link travel costs unconditioned on the occurrence of a substate. Hence, informed drivers need not use the probabilities q, but do use $p_1$ and $p_2$, while uninformed drivers merely use p, which will be split out into q, $p_1$, and $p_2$. The model that follows these principles is given in equations 10 to 12.

$$\begin{aligned} &D_i(N^0_{imp,i}) \le (1-p_0) \bullet C^0(N_{imp,u}+N^0_{imp,i}) + p_0 \bullet C^1(N_{imp,u}+N^0_{imp,i}),\ N_{imp,i}0 \ge 0 \\ &N^0_{imp,i} \bullet (D_i(N^0_{imp,i}) - ((1-p_0) \bullet C^0(N_{imp,u}+N^0_{imp,i}) + p_0 \bullet C^1(N_{imp,u}+N^0_{imp,i}))) = 0 \end{aligned} \tag{10}$$

$$\begin{aligned} &D_i(N^1_{imp,i}) \le (1-p_1) \bullet C^0(N_{imp,u}+N^1_{imp,i}) + p_1 \bullet C^1(N_{imp,u}+N^1_{imp,i}),\ N_{imp,i}1 \ge 0 \\ &N^1_{imp,i} \bullet (D_i(N^1_{imp,i}) - ((1-p_1) \bullet C^0(N_{imp,u}+N^1_{imp,i}) + p_1 \bullet C^1(N_{imp,u}+N^1_{imp,i}))) = 0 \end{aligned} \tag{11}$$

$$\begin{aligned} &N_{imp,u} \cdot (D_u(N_{imp,u}) - ((1-q) \cdot ((1-p_0) \cdot C^0(N_{imp,u}+N^0_{imp,i}) + p_0 \cdot C^1(N_{imp,u}+N^0_{imp,i})) + \\ &\quad q \cdot ((1-p_1) \cdot C^0(N_{imp,u}+N^1_{imp,i}) + p_1 \cdot C^1 N(_{imp,u}+N^1_{imp,i})))) = 0 \end{aligned} \tag{12}$$

It can easily be seen that the above model collapses to the one with perfect information when $p_0$ is equal to 0 and $p_1$ equal to 1. In this situation a substate is identical to the overall state, and hence, the probability p is equal to the probability q. Conversely, when $p_0$ is equal to $p_1$, then the above model collapses to the one without information (and $p=p_0=p_1$). Knowing the prevailing substate is irrelevant in this situation.

## PROPERTIES OF ONE-LINK MODELS

In the current and next sections, we will explore the properties of the models specified in Section 2. In order to keep the analysis manageable and the outcomes tractable we will assume linear demand and cost functions over the relevant ranges considered (that is, the ranges containing the levels of usage in each of the possible states and in each of the possible regulatory regimes). Although the use of linear functions may be criticized, they are in any case sufficient to serve the general goal of the current paper, being enhancing our insight into the welfare economic effects of information provision to a group of drivers. Furthermore, it might be interesting to note that for inelastic demand Arnott et al. (1992) have proven that the equilibrium travel cost functions in Vickrey's dynamic congestion model (Vickrey, 1969) of the morning rush hour with two groups and two parallel routes are special cases of our linear cost functions.

An analytical comparison of the models presented earlier in which information is available, in which no information is present and in which imperfect information is available, leads us to the following proposition for a system with linear demand and cost functions.

Proposition 1: In a one-link network assuming linear demand ($D_i$, $D_u$) and cost ($C^0$, $C^1$) functions, $C^0(N) \leq C^1(N)$, and $dC^0(x)/dx \leq dC^1(x)/dx$, and assuming that the group-route-regularity condition holds, then the following relationships hold:

- expected road usage increases due to information;
- travel costs in state 0 (1) increase (decrease) due to information;
- travel costs in state 1 decrease due to information;
- expected link travel costs decrease due to information;
- the number of uninformed road users in the network increases due to information;
- the expected number of informed road users in the network increases due to information;
- expected welfare increases due to information.

Proof: See Emmerink et al. (1994d, 1995).

Proposition 1 has an interesting interpretation. It tells us that information increases the expected road usage for both the drivers with and without information. However, at the same time the expected travel costs in the network will decrease. Hence, an increase in expected road use is achieved while expected network travel costs have decreased. This result stems from the fact that—when provided with information—more road users will use the network when it is relatively cheap (state 0 occurs), while less informed drivers will use it when it is relatively expensive (state 1 occurs). Moreover, knowing that informed drivers behave in this fashion, more uninformed drivers will also find it profitable to use the network, because the informed drivers will relieve part of the congestion under high cost circumstances (state 1 occurs).

Proposition 1 also shows the relevance of using elastic rather than fixed demand patterns. As shown in Proposition 1, information does in fact alter the system performance even in a one-link network. Under fixed (inelastic) demand however, it is clear that information does not affect the performance of the system, since, independent of the prevailing link travel cost function, the same number of drivers will always use the network.

Even though the above results are appealing, the merits of information provision for government's policy purposes should be based on changes in social welfare rather than on some (derived) performance indicator as expected road usage or expected network travel costs. Social welfare, measured by the total system benefits minus the total (expected) system costs, is the most apt criterion on which to judge the network's performance in terms of efficiency. In addition, equity issues are of course also relevant when analysing the political feasibility of policy measures. Policies that have a strong effect on the current equity situation are likely to provoke resistance. In the next section we will address these issues.

## Efficiency and equity issues of information with cost shocks

The welfare economic aspects of information provision will be studied using the notation subscript p and n to denote the model in which a certain group of drivers is actually informed (p) and the model in which this group i is uninformed (n). Furthermore, a link travel cost function C without superscript denotes the expected link travel costs, ie $C=(1-p)C^0+pC^1$. In the next sections we will confine ourselves to analysing the model with perfect information and the one without information. The features of the model with imperfect information are somewhere in between these two extreme models, see Emmerink et al. (1995). Using Proposition 1, the following relationship for the equilibrium link travel costs is derived:

$$C_n^0 \leq C_p^0 \leq C_p \leq C_n \leq C_p^1 \leq C_n^1 \qquad (13)$$

where these link travel cost functions obviously have to be evaluated at their relevant equilibrium levels of trip demand, for example $C_n^0$ denotes $C_n^0(N_{n,u}+N_{n,i})$. First, the welfare economic impacts of information on the informed drivers will now be discussed.

*Informed Drivers*

The situation for the informed drivers is schematically depicted in Figure 2. In this figure, $D_i$ gives the demand curve, while the horizontal lines denoted C give equilibrium values of costs, and hence should not mistakenly be seen as cost curves.

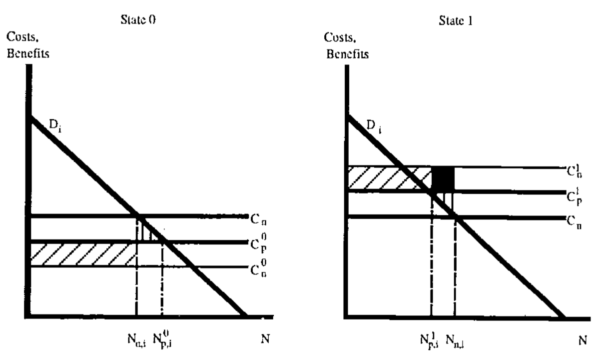


**Figure 2 Welfare effects for informed drivers**

When state 0 occurs, then $N_{n,i}$ is less than or equal to $N_{p,i}^0$ and $C_n^0$ is less than or equal to $C_p^0$. This situation is depicted in the left panel of 2. The drivers on the left-hand side of $N_{n,i}$ will always use the network under state 0. With information provision, their link travel costs will be larger than in the absence of information. Hence, in state 0, these drivers suffer a cost disadvantage that is equal to the size of $C_p^0$ minus $C_n^0$, and is given by the shaded rectangle. It is interesting to point out that this cost disadvantage is an *increasing congestion externality*, since it is caused by the fact that *other* road users are informed. The size of this negative external effect decreases as less drivers have access to the information, since the difference between $C_p^0$ and $C_n^0$ will then decrease.

For the drivers between $N_{n,i}$ and $N_{p,i}^0$, information on the actual occurrence of state 0 induces them to change their behaviour. Without information they will not use the network because expected costs exceed their benefits, whereas they will use the network when they are provided with the information that low costs prevail. The size of the total welfare improvement for drivers between $N_{n,i}$ and $N_{p,i}^0$ is equal to $1/2(N_{p,i}^0-N_{n,i})(C_n-C_p^0)$ and is given by the shaded area in the left panel of

Figure 2. It is important to note that these welfare gains are *internal* in nature, since these arise from better decision-making by the informed drivers themselves. Therefore, we will call these information benefits *internal decision-making benefits*. The size of the internal decision-making benefits decreases as more drivers are informed; with more informed drivers the difference between $C_p^0$ and $C_n^0$ will increase, thereby (ceteris paribus) decreasing the difference between $C_n$ and $C_p^0$. This negative effect for already informed drivers of equipping an additional driver is clearly external in nature. In this state, the marginally equipped driver will gain benefits from the information, while the information benefits for the already equipped drivers will dwindle. (See also Emmerink *et al.* (1994b) where the same phenomenon is discussed.)

If state 1 occurs, then $N_{n,i}$ is greater than or equal to $N_{p,i}^1$ and $C^1(N_{n,i}+N_{n,u})$ is greater than or equal to $C^1(N_{p,u}+N_{p,i}^0)$. The situation is depicted in the right panel of Figure 2. First, drivers on the left-hand side of $N_{p,i}^1$ will always use the network. Owing to the information provision, these will incur benefits equal to the difference in link travel costs $C_n^1$ minus $C_p^1$. This cost advantage is a *decreasing congestion externality*, since it arises from the fact that *other* road users are provided with information and these are lowering link travel demand when state 1 occurs. In the right panel of Figure 2 this external beneficial effect is shown by the large shaded rectangular area. Second, drivers between $N_{p,i}^1$ and $N_{n,i}$ will, knowing that state 1 occurs, change their travel decision and do not use the network. As a consequence, these drivers will benefit from a cost advantage equal to $C_n^1$ minus $C_p^1$, and in addition, from a decision-making advantage equal to the size of $1/2(N_{n,i}-N_{p,i}^1)(C_p^1-C_n)$. Notice that the decision-making advantage is an *internal* effect, while the cost advantage is *external* in nature. The former arises from the fact that the driver himself is informed on the prevailing traffic condition, not from the fact that other drivers are informed. These two beneficial effects are illustrated in the right panel of Figure 2 by the black (coloured) rectangular area (decreasing congestion externality) and the shaded triangular area (decision-making benefits).

In summary, drivers on the left-hand side of $N_{p,i}^1$ (ie drivers who always use the network independent of the occurring state) will suffer from an external cost disadvantage if state 0 occurs and an external cost advantage if state 1 occurs. Drivers between $N_{n,i}$ and $N_{p,i}^0$ benefit from an internal decision advantage if state 0 occurs. Drivers between $N_{p,i}^1$ and $N_{n,i}$ incur an external cost increase if state 0 occurs, and an external cost and internal decision-making advantage if state 1 prevails. Finally, drivers to the right of $N_{p,i}^0$ never use the network and are therefore indifferent between obtaining information or not.

When we consider the equity aspects of information provision in our model, we can derive that no informed individual is worse off due to information provision. Above, it was noticed that informed individuals on the left-hand side of $N_{p,i}^1$ are worse off in state 0 and better off in state 1. In terms of expected individual welfare (net private benefits), however, these drivers are at least as well off as without information, since $C_n$ is larger than or equal to $C_p$ as stated in Proposition 1. Therefore, $p(C_n^1-C_p^1)>(1-p)(C_p^0-C_n^0)$. Using the same argument, it follows that individuals between $N_{p,i}^1$ and $N_{n,i}$ are also better off as they incur the same external cost advantage as drivers to the left-hand side of $N_{p,i}^1$ and in addition benefit from an internal decision-making advantage when state 1 occurs. Informed individuals between $N_{n,i}$ and $N_{p,i}^0$ are also individually better off as they gain when state 0 occurs and are indifferent when state 1 occurs. Finally, individuals to the right-hand side of $N_{p,i}^0$ never use the network and are therefore indifferent between obtaining information or not. *Therefore, in our model the provision of information will always lead to a welfare improvement for the group of informed drivers.* A typical individual (expected) welfare pattern (net private benefits) as generated by our model is shown in the left-hand panel of Figure 3. The shaded area under the bold curve (being equal to the difference between the net expected private benefits with and without information to informed drivers) shows the expected welfare gains.

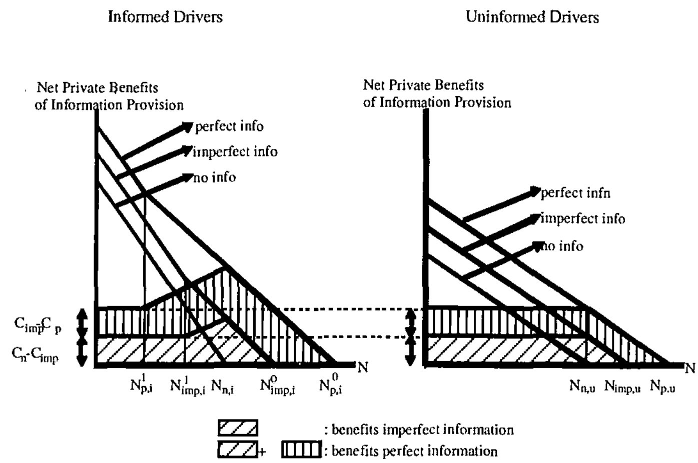


**Figure 3** **Expected net private benefits of information provision for informed and uninformed drivers**

Figure 3 indicates that individuals close to $N_{n,i}$ are best off due to information provision. This is an intuitively appealing result, since individuals close to $N_{n,i}$ are exactly those who doubt most whether or not to use the network. For these individuals, information provision will enhance their knowledge and will affect their travel decisions. On the other hand, individuals on the left-hand side of $N_{p,i}^{1}$ will never change their travel decisions regardless the kind of information provided. Thus it is clear that the information benefits for these drivers are external in nature, ie owing to an improved network efficiency due to information provision to other individuals. Finally, individuals who never use the network have obviously nothing to gain (or lose) from information provision.

*Uninformed drivers*

The situation for the uninformed drivers is schematically depicted in Figure 4. As before, the horizontal lines denote equilibrium values for costs. First of all it is important to note that (following Proposition 1) $N_{n,u}$ is smaller than or equal to $N_{p,u}$, ie the number of uninformed drivers will increase when information is provided to others. Then in state 0, the total benefits minus the total costs for uninformed individuals when no information is provided is shown by the polygon ABCD in the left-hand panel of Figure 4. When information is provided to informed individuals, then the total net benefits for uninformed drivers are given by the polygon AEFG. Hence, in state 0 the change in total welfare for uninformed drivers due to information provision to informed individuals is equal to the surface of the shaded polygon minus the surface of the shaded rectangle in the left-hand panel of Figure 4.

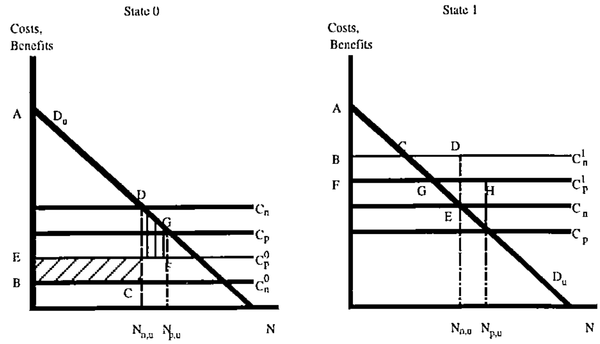


**Figure 4 Welfare effects for uninformed drivers**

When the prevailing network condition is state 1, then changes in total welfare are as depicted in the right-hand panel of Figure 4. Total welfare of the uninformed drivers when no information is available is given by the area ABC minus the area CDE. When information is provided, total welfare changes to the area AFG minus area GHI.

As uninformed individuals between $N_{n,u}$ and $N_{p,u}$ decide to use the network when information is provided to informed individuals, they will experience individual expected benefits; if this were not the case, they would not decide to use the network in the first place. Also, the uninformed drivers on the left-hand side of $N_{n,u}$ benefit from the information provided to informed drivers. This is due to the fact that expected link travel costs decrease when information is provided ($C_p$ is smaller than $C_n$; see Proposition 1). Therefore, *information provision to informed drivers will also lead to a welfare improvement for uninformed drivers* (see also Emmerink et al. 1994b). Clearly, these beneficial effects to uninformed drivers are external in nature; they are induced by behavioural responses from other (the informed) road users. A typical expected welfare pattern for uninformed drivers is shown in the right-hand panel of Figure 3.

*Summary*

In the model presented so far information provision will lead to a strict Pareto improvement: both the informed and uninformed drivers are at least as well off. Due to the provided information the expected road usage will increase, while the expected link travel costs will decrease. Furthermore, we obtain the appealing result that the benefits of providing perfect information exceed those of imperfect information, and that the benefits of providing imperfect information increase as the quality of the imperfect information improves. For the implementation of motorist information systems these results imply that (1) it is always better to provide any (even imperfect) information rather than providing no information as long as the information is consistently unbiased; (2) once this statement is valid it is important to provide as perfect information as possible.

Finally, it is worth noting that these beneficial effects can in theory be reached by providing a very limited amount of drivers with information: only drivers between $N_{p,i}^{1}$ and $N_{p,i}^{0}$ have to receive information to obtain the results discussed in this section, because these are the informed drivers who might change their travel behaviour due to the information on the prevailing link travel cost function. In practice, it is of course hard to identify this group. Although in a free market system with perfect information on the costs and benefits of being provided with traffic information this group of drivers would identify themselves. In such a system, there would also be an exchange of traffic information from informed drivers to uninformed ones. In this way, the number of informed and uninformed drivers would be endogenised.

### System optimal behaviour and information provision with cost shocks

In the previous section the important result was obtained that information provision in a one-link network leads to a strict Pareto improvement. In the current section we will address the size of this efficiency improvement on the basis of some experiments. We will do so by comparing the effects on total (expected) welfare of the following three regimes:

- information provision
- no information
- system optimal behaviour.

Under system optimal behaviour, the number of individuals using the network is derived in such a manner that total expected welfare, as measured by total system benefits minus total expected system costs, is maximised. It is well known that this can (in theory) be implemented by a fluctuating congestion-pricing scheme.

The effects of these regimes on expected welfare are captured in the performance indicator $\omega$ (see Arnott et al. 1991; Verhoef et al. 1994b), which in the present paper indicates the relative welfare improvement of providing information to a group of drivers. The index $\omega$ is defined as:

$$\omega = \frac{\text{Welfare(Information) - Welfare(No Information)}}{\text{Welfare(Optimum) - Welfare(No Information)}} \qquad (14)$$

Hence, $\omega$ gives the achievable welfare gains as a proportion of the theoretically possible welfare gains. Clearly, $\omega$ cannot exceed the value one. In addition, $\omega$ cannot be smaller than zero, since it was shown in the previous section that information provision leads to a strict Pareto improvement, implying that the numerator of expression 14 cannot take on negative values.

Below, due to reasons of space, only the most interesting model experiments will be verbally presented. For a more rigorous analysis, the reader is referred to Emmerink et al. (1994d, 1995).

- The indicator of relative welfare improvement $\omega$ ranges between 0 and 0.4.
- The larger the stochastic cost shock, the more efficient information provision.
- $\omega$ increases as more drivers are informed; however, this increase takes place at a decreasing rate.
- The impact of the slope of the demand function is rather complex. Information seems to be most efficient at intermediate demand elasticities.

To conclude, the experiments have taught us that the size of the welfare improving properties of information provision depend on a number of complex interactions between the probability of having a non-recurrent incident, the impact of such an incident, the slope of the demand function, and the respective group sizes of informed and uninformed drivers. Our experiments suggest that for a linear system the maximum achievable welfare gains, expressed as a proportion of the theoretically possible efficiency gains, will most likely not exceed 0.4. $\omega$-values exceeding 0.4 can be obtained by (practically) inelastic demand. However, the absolute welfare gains are converging to zero under these circumstances.

## CONCLUSION

In this paper, we studied the welfare economic effects of information provision to a group of drivers. We did so by building an equilibrium model with elastic demand for road usage. The model was introduced in a one-link network with two groups of (potential) users, informed and uninformed ones. Informed users base their decisions on actual prevailing traffic conditions, while uninformed drivers use expected traffic conditions. We considered non-recurrent congestion caused by shocks in the link travel cost function.

It was found that the provision of perfect and imperfect information is welfare improving for both the informed and uninformed drivers. Hence, information leads in our model to a strict Pareto improvement. The results suggest that it is always beneficial to provide any (even imperfect) information rather than to provide no information at all. With information provision, the user equilibrium is nearer to the system optimum. Information provision will however, not close the gap between the two concepts. Even when all road users are well informed, the user equilibrium will still be different from the system optimum.

Furthermore, the analysis showed that many of the beneficial effects (and some of the adverse effects) of information provision are external in nature; they arise from changes in trip-making decisions by others. For example, the beneficial effects of information provision to uninformed drivers are clearly external in nature. They arise from behavioural adaptations by the informed drivers, rather than from changes in travel decisions by the uninformed road users. The existence of these external effects raises an interesting question about the government's role in introducing these technologies. It is well known that without proper government intervention, external effects distort the market mechanism, and result in an inefficient allocation of scarce resources.

In contrast to most of the literature on the impacts of information provision, our equilibrium model allows for elastic demand. In doing so, we acknowledge the important economic relationship between demand and supply. The results in this paper indicate that the elasticity of demand is an important factor in determining the welfare improving properties of information provision. Information was found to be less useful at both low and high levels of demand elasticity.

Various research issues have to be dealt with in the future. First, it is important to extend the analysis to more general networks. Second, it would be interesting to endogenise the choice of being informed. Thus far we have assumed that the population consists of two mutual disjoint groups of drivers, informed and uninformed ones. It is of course more realistic to assume that the choice of being informed depends on the expected benefits, rather than being an exogenous input. Finally, the present analysis has ignored the additional beneficial effect that information provision might reduce drivers' perceptual errors regarding traffic conditions. In our model we have assumed that potential road users are perfectly aware of average network conditions. It is however, not directly obvious what the consequences of relaxing this assumption are.

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