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**Author(s):**
Rietveld, Piet; Emmerink, Richard H.M.; Axhausen, Kay W. ; Nijkamp, Peter

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# CONCENTRATION, OVERREACTION, MARKET PENETRATION AND WARDROP'S PRINCIPLES IN AN ATIS ENVIRONMENT (*)

R.H.M. EMMERINK
K.W. AXHAUSEN
P. NIJKAMP
P. RIETVELD (**)

ABSTRACT: In the literature on the implementation and use of Advanced Traveller Information Systems (ATIS) it has been acknowledged that information provision in road transport networks might have unexpected behavioural consequences and cause adverse effects on network performance. In particular, due to concentration and overreaction of road users, the congestion relieving effects of these advanced technologies might be small in practice. To successfully implement ATIS, a more substantial understanding of these phenomena is essential.

This paper investigates behavioural overreaction and concentration from a theoretical perspective, and relates it to the level of market penetration of the new technology, i.e. the percentage of drivers equipped with ATIS. In addition, the role of Wardrop's two princi-

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(**) *Richard H.M. Emmerink is affiliated with the Tinbergen Institute and the Department of Regional Economics, Faculty of Economics and Econometrics, Free University, Amsterdam; Peter Nijkamp and Piet Rietveld are affiliated to the latter institution; Kay W. Axhausen is at the Centre for Transport Studies, Department of Civil Engineering, Imperial College, London.*

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ples, viz. the user equilibrium and the system optimum, with respect to ATIS is analysed. It turns out that the level and/or reliability of information is critical.

It is concluded that the application of ATIS with imperfect information will not lead to the system optimum; then a congestion-pricing policy is needed to achieve this. However, ATIS and congestion-pricing are not by definition competing tools, but can well be used as complements. Furthermore, it is argued that overreaction is strongly dependent upon the level of market penetration of the information technology at hand. And additionally, that the optimal level of market penetration is highly dependent upon the kind and quality of the information provided. More research in this direction, and specifically in the simultaneous application of congestion-pricing and ATIS, is needed.

## 1. INTRODUCTION

In recent years much attention has been given to ways of increasing the capacity of transport networks by providing relevant information on actual or expected road conditions to the users. Such a rise in performance of infrastructure is not only important from an efficiency perspective, but may also alleviate congestion, environmental pollution and accident rates. As a consequence, in both the US and in Europe major traveller information systems are at present being designed and experimented, witness the US IVHS and the European DRIVE programme on telematics. However, as pointed out by Ben-Akiva et al. (1991), the application of information provision to drivers in road transport networks may have negative effects on network performance, if saturation, overreaction or concentration takes place. Greater understanding of these phenomena and their relationship with the level of market penetration (the percentage of drivers provided with information) is essential for the successful implementation of Advanced Traveller Information Systems (ATIS). This paper addresses this issue and, in addition, investigates the role of Wardrop's principles, the user equilibrium and the system optimum, in an ATIS environment. Besides, also the issue of market penetration is covered.

The paper is organised as follows. Section 2 is devoted to clarifying the terms overreaction and concentration, respectively. Section 3 investigates the role of Wardrop's principles, while the relationship between overreaction, concentration, Wardrop's principles and the level of market penetration is explored in Section 4. Finally, Section 5 contains some concluding comments and identifies further research directions.

## 2. BACKGROUND

### 2.1. *Adverse effects of ATIS*

In general, ATIS serves to increase the efficiency of transport networks and to alleviate negative externalities of transport behaviour. In the literature it has been recognised that ATIS could have adverse effects on the overall performance of a transport network (Arnott et al., 1991; Ben-Akiva et al., 1991; De Palma, 1992). Arguments supporting this possibility can, roughly speaking, be subdivided into two classes of conditions:

- phenomena related to imperfect information;
- phenomena regarding the behavioural response of drivers towards the information.

The former case has been investigated by Arnott et al. (1991); their research confirmed that particularly imperfect information could potentially lead to a worsening of actual network performance. Phenomena related to behavioural responses that may negate some of the beneficial effects of ATIS are mentioned in Ben-Akiva et al. (1991). They list three potential adverse effects of information provision:

- oversaturation
- overreaction
- concentration.

Oversaturation occurs if drivers are unable to process the supplied information properly/rationally. For instance, information could overload the driver, thus distracting and impairing him from selecting the optimal route. As pointed out by Ben-Akiva et al. (1991), this is mainly a psychological-technical man-machine interaction problem which can in principle be overcome and will not be discussed further in this paper. In Sections 2.2 and 2.3 the discussion will be focused on the two remaining issues of overreaction and concentration, respectively.

### 2.2. *Description of overreaction*

A major potential flaw of ATIS is the possibility of overreaction. The phenomenon of *overreaction* has been mentioned repeatedly in the literature. Most rigorously it has been described by Ben-Akiva et al. (1991). In this section their description of overreaction forms the starting point of an analysis.

Ben-Akiva et al. (1991) describe overreaction as:

> "... a situation in which a substantial fraction of drivers receive information on traffic conditions. Overreaction occurs when drivers' reactions to traffic information cause congestion to transfer from one road to another. It may also generate oscillations in road usage. Overreaction may happen if too many drivers respond to information on current traffic conditions.
>
> When current traffic information is provided to drivers, overreaction may be avoided if drivers' decisions are based on correct expectations of the other drivers' reactions. For example, some drivers may not shift to a reportedly faster route because they anticipate a rush of the other drivers to that route. Overreaction is likely to take place if drivers fail to consider or underestimate the potential responses of the other drivers. The task of anticipating the other drivers' responses is difficult to perform.
>
> ...
>
> Overreaction may also occur when predictive information or route guidance is provided to drivers. However, in this case part of the blame for overreaction lies in the failure of the information provider to accurately predict driver behavior and reaction to information, including an estimate of the fraction of drivers who will follow the advice. This results in an inconsistency between predicted and realized traffic conditions" (p. 254).

They support their case with the example of holiday makers who overreact to supplied information on how to plan their journey optimally. Clearly, this kind of information is static in the sense that it is received some time before the journey is undertaken. In addition, exactly the same information is given to all holiday makers. As will be argued in Section 4.3, overreaction is not restricted to static information, but can occur with real-time – or even predicted – information as well.

From the description above, it follows that if overreaction takes place, some roads will be overused, while at the same time others will be underused. The travel time on the overused routes will obviously be larger than the travel time on the underused ones. By definition, this implies that the conditions for the *user equilibrium* (Wardrop's first principle) are not met, since the user equilibrium (see Wardrop, 1952) assumes that:

> "The journey times on all the routes actually used are equal, and less

than those which would be experienced by a single vehicle on any unused route" (p. 345).

In addition, it is clear that overreaction deals with a situation in which drivers are unable to correctly predict the responses of those drivers provided with the same information, and therefore causes congestion on some roads to be more severe than on others. In other terms, the information supplied to the drivers is imperfect in the sense that drivers still need to predict the responses of other drivers to the information (1). In this respect it can be argued that overreaction is the consequence of providing imperfect information to the drivers or digesting actual information without including behavioural responses of other road users. Thus, overreaction is essentially the result of a partial equilibrium approach without the inclusion of sufficient positive and negative *feedback* and *feedforward* mechanisms.

Furthermore, it is fruitful to address the inter-relationship between the congestion externality and overreaction.

- The congestion externality is caused by the fact that drivers do not take into account the impacts of their own decisions on the trips of other drivers during their decision-making process. This kind of behaviour leads to the user equilibrium in the network and *is* optimal from an individual perspective. However, from a collective perspective, this situation *is not* optimal if the user equilibrium does not coincide with the *system optimum* (a situation in which "The average journey time is a minimum", Wardrop (1952, p. 345)) which is generally the case in congested networks (Sheffi, 1985).
- The phenomenon of overreaction occurs if drivers fail to take into account the responses of the other road users to the information provided. This leads to a sub-optimal decision from an individual point of view.

Summarising, we may claim that for a driver to behave optimally from an individual point of view, his decision-making process *should not* take into account the implications of his behaviour for other drivers, but it *should* take into account the decisions of other drivers. If all drivers suc-

(1) In this paper, imperfect information refers to information that is not perfectly predictive.

ceed in doing so, the situation in the network will be represented by the user equilibrium.

Whether the implications of overreaction are severe, mainly depends upon the degree of *irreversibility* of the decisions made by the drivers. If a *wrong* decision, due to overreaction, cannot be reversed, the full cost consequence of this decision have to be borne. However, if a decision can partly be altered after some of the consequences have been experienced, overreaction has evidently a less serious impact. An irreversible decision can be illustrated by a departure time decision. Once a driver has started his trip, the departure time cannot be changed. A reversible decision is, for instance, a route choice decision with options to switch to other available routes during the trip. It should be noted however, that in case of reversible decisions also all other road users may adjust their behaviour, so that at the end still severe adverse impacts might be expected.

## 2.3. *Description of concentration*

Concentration is a related concept frustrating the potential of ATIS. Ben-Akiva et al. (1991, p. 254) describe *concentration* as follows.

> "In general, a group of drivers travelling from an origin to a destination tend to use different routes and departure times because they have heterogeneous preferences and diverse perceptions of network conditions. Differences between perceived and actual network conditions imply that drivers who are not well informed may select alternatives which are not in their best interest. Information tends to reduce the variations among drivers because it increases uniformity of perceptions of network conditions around the true values. As a result a greater number of drivers may select the best alternatives (from their individual point of view) and consequently drivers with similar preferences will tend to concentrate on the same routes during the same departure times. Thus, more information could potentially generate higher levels of traffic congestion".

Ben-Akiva et al. (1991) illustrate the situation of concentration by means of an example in which the initial situation in the network (without information) leads to a better system performance than the situation with information in which they assumed that the user equilibrium would result. Thus, concentration occurs if differences in drivers' perceptions are reduced due to information provision. As a consequence, some drivers will make *better* decisions from an individual point of view, but the situation in the network as a whole will be *worse*. Thus, concentration may drive the transport system even further away from Pareto optimality. Consequently, it may now be interesting to look more carefully into the essential elements of both Wardrop's principles.

## 3. WARDROP'S PRINCIPLES

In this section we will discuss the user equilibrium case (Wardrop's first principle) and the system optimum (Wardrop's second principle), respectively.

### 3.1. *The role of Wardrop's first principle: the user equilibrium*

It is well known from economic forecasting that each future forecast may lead to behavioural responses that make the original forecast futile. The example given in the previous section addresses in this context a crucial point. If *perfect predictive information* is supplied and it is assumed that drivers behave accordingly *rational*, it is reasonable to assume that the *user equilibrium* according to Wardrop (1952) results. Here, perfect predictive information is defined as predictive information that will appear to be correct in the future. Provision of perfect predictive information is, however, a highly hypothetical case because it requires the provider of the information to perfectly forecast the drivers' responses towards the information. This is an unrealistic assumption since, to be able to provide perfect predictive information, drivers' responses towards the information need to be known in advance, while these responses, in turn, depend upon the information provided. Figure 1 shows the vicious circle between predictive information and drivers' responses, and illustrates that *as soon as the predictive information is given new predictions have to be made.*

Perfect predictive information possesses the property that the information remains correct after the drivers' responses. Figure 2 shows an iterative hypothetical method for obtaining perfect predictive information

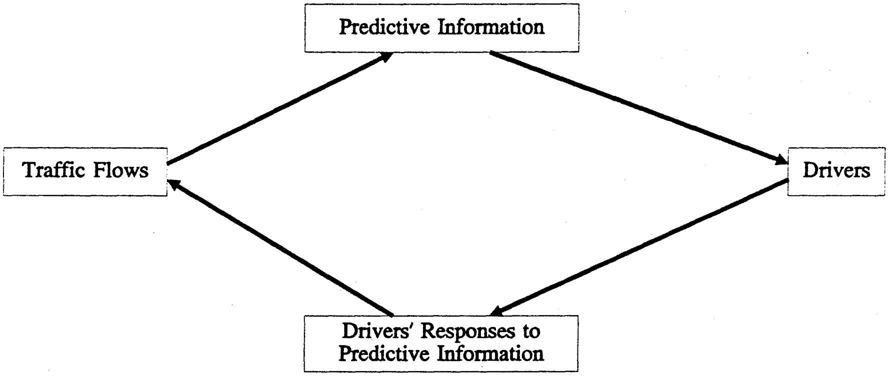


Figure 1 – Predictive information and drivers' responses.

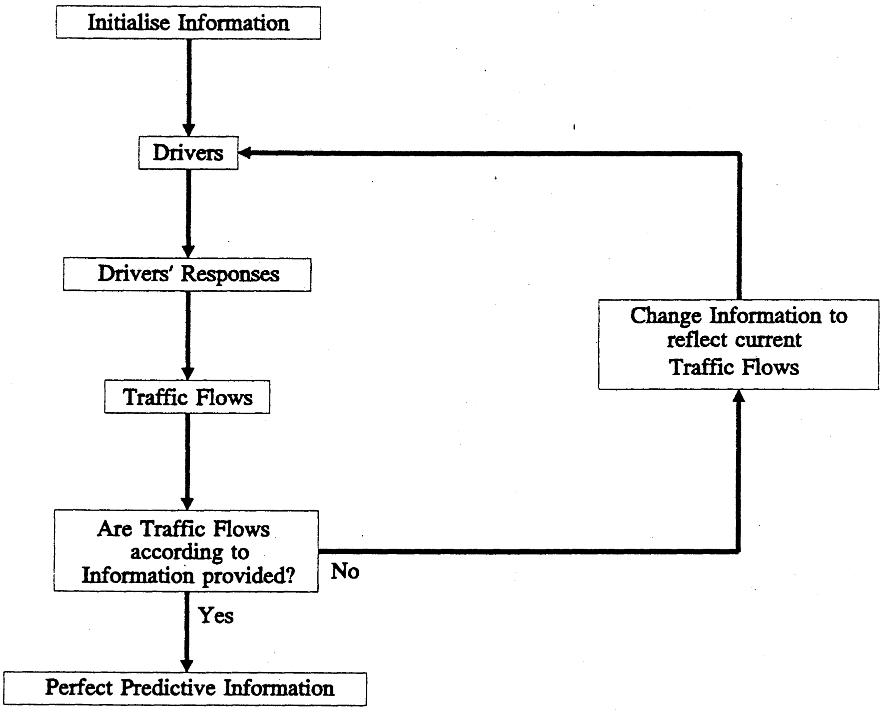


Figure 2 – Iterative procedure for calculating perfect predictive information.

(2). Here, it is assumed that the provider of the information knows the drivers' responses with certainty.

Information reflecting the traffic situation at user equilibrium is ceteris paribus perfectly predictive. This can easily be checked with Figure 2. At user equilibrium none of the drivers has an incentive to change routes since they will be worse off by doing so. In addition, this is the only kind of information having this property. This can be clarified as follows.

> Suppose that information is perfectly predictive, but does not reflect traffic flows at user equilibrium. Then, some drivers will be better off by not complying with the information. Therefore, the traffic flows, after having provided the information, will not reflect the given information, and hence, the information is not perfectly predictive.

The argument above provides another justification for assuming Wardrop's user equilibrium if perfect predictive information is supplied and can be summarised as follows:

> *Perfect predictive information reflects the user equilibrium and leads to traffic flows equivalent to the user equilibrium.*

This proposition leads to an important consequence: if we assume that the situation in a road transport network without ATIS is represented by the user equilibrium, then there is no potential gain of ATIS which provides perfect predictive information.

Nevertheless, Wardrop's first principle has, despite some shortcomings as illustrated by the well-known Braess paradox (3) (cf. Braess, 1968; Frank, 1981), been widely accepted as giving a reasonable approximation of the prevailing situation in road transport networks without ATIS, and has been used repeatedly in much empirical work (4). Recently, some

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(2) Practical work, trying to model and predict traffic conditions on a highway network in real time, is currently being carried out in the DRIVE project DYNA; see Lindveld et al. (1992). Recently, Koutsopoulos and Xu (1993) wrote a paper addressing the prediction of travel times.

(3) Braess showed that the addition of an extra link in a network could lead to a larger average (system wide) travel time under the user equilibrium principle.

(4) In particular, the user equilibrium is widely used in the assignment phase of the four-step modelling process.

researchers have questioned the appropriateness of the user equilibrium. Here, two arguments will concisely be discussed.

Firstly, Horowitz (1985) has argued that if link costs are flow dependent (as they are in real-life networks), travellers are unlikely to know the costs of a trip before it is actually taken. Rather, they must estimate the costs from past experience with the network. It can be shown (Horowitz, 1984) that depending on the drivers' information about the network's performance in the past, and the way they use the information to estimate the costs of a current trip, traffic flows may converge to their equilibrium values, oscillate around these values perpetually or converge to values that depend upon the initial conditions and may be considerably different from the user equilibrium. As pointed out by Dehoux and Toint (1991), the assumption needed for the application of the user equilibrium (viz. everyone has complete knowledge on the situation in the network), is not met in real-life transport networks. On the contrary, this is exactly what ATIS would like to achieve.

Secondly, Dehoux and Toint (1991) have claimed that one of the purposes of the application of systems that provide information to drivers is to produce substantial changes in traffic patterns over short periods of time in order to resolve traffic jams more quickly. Such situations, often referred to as non-recurrent congestion, do not fit into an equilibrium framework, since traffic flows will deviate from their equilibrium values during these periods. In view of these arguments, instead of an equilibrium principle, Dehoux and Toint (1991) proposed *behavioural rules* that could vary from one group of users to the next in order to capture some of the wide behavioural variations between drivers. The kernel of their approach thus consists of a *behavioural framework*. A similar modelling methodology has recently been proposed by Watling and Van Vuren (1993). They argued that the component *driver behaviour* (Watling and Van Vuren, 1993, Figure 1, p. 162) is one of the three key components of ATIS. Research according to this approach has been conducted by several authors. We refer here for instance to the work of Iida et al. (1992), Mahmassani and co-authors (summarised in Mahmassani and Herman (1990)) and Stern et al. (1990).

### 3.2. *The role of Wardrop's second principle: the system optimum*

An important question is whether there are tools to achieve an optimal performance of a transport system. Wardrop's second principle (see the quotation in Section 2.2), known in the literature as the system optimum, is the situation in which total travel time in the network is minimised. In congested networks, the system optimum will not coincide with the user equilibrium (cf. Sheffi (1985)). Furthermore, Mahmassani and Peeta (1993) found that the discrepancy between the system optimum and the user equilibrium can be large in heavily congested (though not oversaturated) networks. If it is the government's aim to achieve the system optimum in road transport networks, an effective policy is required. Given the arguments in the previous section, it is unrealistic to believe that ATIS is such a policy. It was seen that perfect predictive information leads to the user equilibrium, and therefore a kind of imperfect information should be provided to the drivers. However, as Bonsall et al. (1991) point out, it is not very likely that drivers will comply with imperfect information; they will tend to ignore it. In particular, given that drivers are able to assess the reliability of information (Vaughn et al., 1992), it is unlikely that the system optimum will be reached by providing imperfect information.

Hence, an alternative policy is required. The *best*, from a theoretical point of view, is the implementation of a congestion-pricing scheme. Such a policy charges the drivers for the difference between the marginal social and marginal private costs, and leads to the system optimum. However, implementing congestion-pricing is difficult in practice (5). Even if the technology required for electronic congestion-pricing were available, the implementation is not straightforward. The reason is that the optimal charge of a trip is dependent upon the level of congestion on the roads at the time of use. Therefore, the precise charge cannot be known prior to the trip. In such a situation, ATIS could provide drivers with information and, based upon this, a predicted charge for each route. The driver could then make a trade-off between the costs and travel time associated with the trip of the alternative routes. Therefore, it is plausible that ATIS could

(5) In addition, public and political support for congestion-pricing is still relatively small. See for instance Jones (1991).

be an important complement to an advanced congestion-pricing scheme. More research in this direction is clearly needed. The contribution by De Palma and Lindsey (1992) is for the time being the only one addressing the simultaneous implementation of ATIS and congestion-pricing.

## 4. CONCENTRATION, MARKET PENETRATION AND OVER-REACTION: FURTHER THOUGHTS

In this section a further substantive intepretation of Wardrop's principles and its relationships to concentration, adoption of information and overreaction will be given.

### 4.1. *Relationship between Wardrop's principles and concentration*

Under the assumption discussed in the previous section, that the user equilibrium corresponds to a situation in a network where perfect predictive information is provided, the phenomenon of concentration can be described in terms of both the system optimum and the user equilibrium (i.e., both Wardrop's principles).

Let us denote by *T(system optimum)* the average travel time in the system at system optimum, *T(user equilibrium)* the average travel time at user equilibrium, and *T(initial)* the average travel time in the system without information. Furthermore, we assume that *T(information)* is the average travel time in the network under the perfect predictive information case.

Clearly, *T(initial)* is equal to the average travel time in the system under the initial conditions, or in other terms, the average travel time associated with the initial route and departure time decisions of the drivers in the network. Then it can easily be seen that concentration occurs if relation [1] holds.

$$T(\text{system optimum}) \leqslant T(\text{initial}) \leqslant T(\text{user equilibrium}) \qquad [1]$$

It is easily seen that in this situation, supplying perfect predictive information, which by assumption makes *T(information)* equal to *T(user* *equilibrium)*, leads to a worsening in network performance. However, if relation [2] holds

$$T(\text{system optimum}) \leqslant T(\text{user equilibrium}) \leqslant T(\text{initial}) \qquad [2]$$

provision of perfect predictive information increases the network performance, since it brings the average travel time down to the average travel time at user equilibrium, which is in this case smaller than the average travel time under the initial conditions.

The example given in Ben-Akiva et al. (1991) – mentioned in this paper in Section 2.3 – illustrates clearly these relationships. Another example taken from a game-theoretic context can be found in De Palma (1992). De Palma models the traffic flows in a transport network as a game between two drivers (two players). In this two-player game, he shows that under certain regimes (certain values of the entries in the payoff matrix) information provision can shift the outcome of the play to a Nash equilibrium unequal to the system optimum, thereby decreasing social welfare (6).

The analysis in this section, stresses two important points with respect to the effectiveness of perfect predictive information in a world with rational (utility maximising) drivers, viz.:

- whether the information will be beneficial depends solely on the system performance under the initial conditions and at user equilibrium;
- the potential additional benefits of supplying system optimal information depends on the difference in travel time between system optimum and user equilibrium.

The first point, the importance of the initial situation in the network, has been recognized by Mahmassani and Jayakrishnan (1991) and Mahmassani and Chen (1991). Their simulation experiments suggested that the usefulness of information provision was strongly dependent upon the initial conditions in the network, thereby underlining the arguments given in this section. Given the arguments in Section 3.2, it is unlikely that

(6) The Nash equilibrium may be regarded as being the game-theoretic equivalent of the user equilibrium. In game theory, a situation is a Nash equilibrium if the players respond optimally to each others' strategies.

drivers will follow system optimal routes if that will lead to an increase in their own travel time. This means that a combination of congestion-pricing and ATIS will then be needed to reach the system optimum.

### 4.2. *Market penetration and concentration*

A major issue on the impact of information is the access to or user acceptance of ATIS. In the theoretical exposition given in Sections 2.2, 2.3, and 4.1, the term market penetration or adoption of (telematics) information has not been used. The discussion which level of market penetration is best is irrelevant in a world with perfect predictive information and rationally behaving drivers. The situation with the smallest average travel time will always be reached at a market penetration level equal to 100 per cent if relation [2] in Section 4.1 holds; next, if relation [1] holds, the situation will be worst if the level of market penetration equals 100 per cent.

If the information provided is not perfectly predictive, the situation becomes more complicated. In general, given the arguments in Section 3.1, one could argue that the purpose of any kind of information provision system is to get closer to the user equilibrium. As a consequence, if relation [1] holds, one should be very careful in providing information, since even if the information is not perfectly predictive, it will show a tendency to worsen the network performance.

Therefore, we may conclude that, if relation [1] holds, information provision will lead to concentration and should therefore not be given. From this perspective, it is important to analyse whether prevailing situations (initial conditions) in real network are represented by relation [1] or [2], as this is decisive for the network performance of ATIS.

### 4.3. *Market penetration and overreaction*

In contrast to the previous section, the level of market penetration becomes crucial in situations with overreaction. The difference between overreaction and concentration is underlined by a citation taken from Ben-Akiva et al. (1991):

> "Concentration is intrinsic to any system and holds even with perfectly rational drivers. Overreaction is a consequence of the fact that the drivers and/or the drivers information system are unable to perfectly forecast the use of information by all drivers" (p. 254).

In light of these differences it is evident that concentration can take place even with perfect predictive information and rational drivers (as shown in Section 4.1), while overreaction is a consequence of either imperfect information or irrational drivers. If perfect predictive information is given to rational drivers, overreaction cannot occur, since the perfect predictive information reflects, by definition, the situation in the network at any time in the future, and therefore takes into account the responses of all drivers towards the information provided. The driver simply has to choose his alternative according to the information and does not have to worry about the impacts of the decisions of other drivers on his trip, since these are incorporated in the supplied perfect predictive information.

However, as illustrated in Section 3.1, the provision of perfect predictive information is highly hypothetical. In any real-world situation there will be some uncertainty regarding drivers' responses to the information, hence making the information imperfect. As a consequence, one should be very careful in providing information (cf. Arnott et al., 1991). The full impacts of overreaction should be acknowledged and it is at this point that the issue of market penetration enters the discussion.

Overreaction taking place at a relatively low level of market penetration will not dramatically affect the situation in the network. Stronger even, as long as the benefits due to the information provision exceed the negative impacts of the overreaction (also due to the information provision), the network performance will improve. Therefore, the resulting situation in the network after the provision of information is a trade-off between the positive effects of the information (the fact that the drivers are told where the congestion takes place) and the negative effects (the fact that too many drivers change routes to the uncongested route, thereby shifting the congestion).

At a low level of market penetration the positive effects will outweigh the negative effects of overreaction. As the level of market penetration increases, the negative effects of overreaction will become more severe and will eventually outweigh the benefits generated by ATIS. In such a situation, according to economic principles, the optimal level of market penetration is the level at which the marginal benefits of the information are equal to the marginal costs due to overreaction. However, in practice this level of market penetration may be hard to find, and additionally, it may be dependent upon both the network and the kind of information provided.

On theoretical grounds, one could argue that more reliable information allows a higher level of market penetration, a situation which is underlined by the findings in Emmerink (1993). He found that the optimal level of maket penetration is close to twenty per cent if after-trip information (information given to the drivers on the situation in the network during the last travel period) is supplied, while real-time en-route information permits a significantly higher level of market penetration. This stresses the importance of the quality of traveller's information. High quality information, being informative and accurate, seems to allow a relatively high level of market penetration; low quality information causes overreaction taking place already at low levels of market penetration. This trade-off between the level of market penetration and the quality of the information has as yet been given sparse attention in transport and telematics research. However, if the technological ability of ATIS does not allow continuous information updating, the question of the quality of the information, which in turn is directly related to the updating frequency of the information, becomes a crucial one. More research should thus be directed to the sensitivity of overreaction with respect to the updating frequency of the information and the level of market penetration.

## 5. CONCLUDING COMMENTS AND FURTHER RESEARCH DIRECTIONS

Overreaction and concentration are two phenomena, which can both adversely affect the success of ATIS. Concentration can take place in any network and is not due to irrational behaviour, while overreaction is caused by a form of imperfect information (or in a way irrational behaviour).

If perfect predictive information is supplied to the drivers it is reasonable to assume that the user equilibrium in a road transport network will result. However, the user equilibrium is not an appropriate reflection of the situation in the network if imperfect information is supplied to the drivers. Moreover, ATIS itself is not sufficient to reach the system optimum. A policy of congestion-pricing in combination with ATIS is then needed to achieve this. More research in the simultaneous application of congestion-pricing and ATIS is needed.

Due to concentration, the overall performance of the network may be worse off compared to the initial situation in the network if perfect predictive information is provided. In these circumstances, the initial situation in the network falls in between the system optimum and the user equilibrium. As a consequence, it is important to analyse the initial situation in real-world road transport networks, in order to determine whether concentration will take place if ATIS is implemented.

The issue of market penetration is not directly related to concentration. However, it is very important with respect to overreaction. A high level of market penetration may significantly affect the situation in the network, while a low level may improve the network's performance. It goes without saying that more insight needs to be gained into the relationship between market penetration and overraction and the dependency of this relationship on both the kind and the quality of the information provided.

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