The effects of ATIS on transportation systems: theoretical analysis and numerical applications

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Abstract

In this paper some of the inconsistencies and limitations of other models in the simulation of the effects of ATIS (Advanced Traveller Information Systems) will be discussed, with particular regard to the impact of pre-trip information on the day-to-day dynamics of transportation systems. An innovative model will be proposed, where the compliance of travellers to ATIS will be considered to be elastic and explicitly modelled; it will be considered both variable within the whole dynamic process and dependent on the accuracy of the information. For the sake of simplicity, a fixed O/D demand will be considered and the effects of ATIS will be taken into account only on route choices. It will be shown that in most cases ATIS cannot be used to optimise the performances of the traffic network (system optimum); rather, travellers are compliant to information only if supplied according to user optimum. The main role of ATIS in recurrent traffic conditions will be shown to be the stabilisation of the transport systems.

The first section will introduce the motivations of the proposed model and how they have been addressed in literature, moreover it will anticipate most of the innovative characteristic of the proposed model, as well as the expected accuracy of the results. In the second section the model will be formalised as a dynamic process, which includes explicit simulation of compliance. In the third section the result of some numerical experiments, related to different information strategies, will be presented; moreover, some theoretical analysis will be carried out by determining the stability domain for the dynamic process in presence of information.

Keywords: dynamic traffic assignment (DTA), advanced traveller information systems (ATIS), day-to-day dynamics, user Optimum.



1 Introduction and state of the art

In last decades ATIS applications have been among the most popular issues for transportation analysts and many models have been proposed and discussed because of the expectation of many analysts to solve with minor infrastructural investments several of the oversaturation problems concerning traffic. Moreover, traffic information is also from a commercial point of view a valuable content for modern applications in the field of telecommunications and some study have shown that travellers exhibit a relevant willingness to pay for accurate and advanced traffic information (Khattak et al. [1]). This paper aims to investigate and, if possible, to prove some conjectures: (a) ATIS applications cannot be used, in general cases, to reach system-optimum performances; (b) several information strategies can be implemented and their effects can be significantly different; (c) models for the computation of ATIS' effects should be comprehensive of the explicit and elastic simulation of the equipped travellers' compliance; moreover the compliance should be related to the accuracy of the information, in order to avoid the incorrect determination of the effects and of the role of ATIS' market penetration.

ATIS are intrinsically integrated with advanced communication platforms and devices, and are aimed to increase (or integrate) the information level on network conditions that most of the travellers already have from their own traffic estimation process (experience): they add "technological information" to the "natural information". Information contents are gathered, elaborated and delivered by traffic-centrals able to increase the accuracy and the effectiveness of (real-time) monitored traffic data. Several technologies can be used to supply information, these technological aspects could differently characterise practical applications of ATIS. In this paper it is assumed that the delivering technology is based on personal communication devices (at home or on-board) and massive use of pervading telematics. Travellers equipped with personal traffic information devices will be denoted as "equipped", while others will be denoted as "non equipped". Extension of the analysis and of the results of this paper to more "traditional" communication devices (VMS, radio, TV) is possible but not trivial. A crucial point is that also non-equipped travellers are "naturally informed"; moreover, in equilibrium conditions non-equipped travellers own a "correct" information (a part from stochastic dispersion), while in dynamic conditions non-equipped travellers day-to-day update their information toward the correct one.

A presentation of the literature related to models for ATIS can be found in papers [2] and [3] as well as in their references. Our opinion is that the development of effective models for ATIS has been negatively influenced by a crucial misunderstanding, that is the assumption that information from ATIS could induce travellers to behave according to system-optimum or, which is similar, could create the conditions for the coincidence of users-optimum and system-optimum. Such a point of view has induced analysts as (for example) Mahamassany and Peeta [4] to measure the advantages of ATIS applications in terms of saved travel-time on the whole network, or others ([5] and [6]) to define



the distance between user-optimum and system-optimum as the greatest potential advantage. This same misunderstanding has induced to consider the problem of designing and assessment of ATIS systems as a classical control problem not really different from the problem of ATMS (Advanced Traffic Management Systems), where: (i) the objective function is a measure of the total network travel time (or it is related to this) for all users (or only for equipped users), (ii) the control variables are the delivered information (or the induced turning-rates). An extreme consequence of that can be observed in Weymann et al. [7]; they face the problem with any regard to real congestion phenomena, dynamic and/or equilibrium issues and travellers' behaviours. Similarly, in the paper by Thakuriah and Sen [8], the information strategies are based on statistic and descriptive considerations, with no regard to: (a) travellers' reaction to information; (b) a clear view of the field of appliance and of the suitable objectives of an ATIS implementation; (c) the strong relation (as it should be expected) between the accuracy of the information (the reliability for users of the information and the usefulness of the information in terms of travellers' satisfaction). We argue that the real reason that has induced the above described misunderstanding is due to an incorrect approach to travellers' compliance to ATIS. Compliance has been often considered as a sort of exogenous disturbance factor in the models, in the sense that it has been considered to be non controllable and, in same sense, intrinsic and fixed in the travellers' behaviour. With such an approach, ATIS models use the compliance has a fixed value or, in more sophisticated studies, ATIS performances have been studied with respect to parametric variations of the compliance. It is evident that in such a case (with exogenous compliance values) ATIS can be used as "regulators" in order to reach a system optimum; travellers, in such a case, are simulated to react to information also if not supplied according to user optimum; this is, obviously not the case of the real world, where travellers tend to ignore not satisfactory information. Such an approach is followed by Mahmassani in [9] and successive papers; he uses a sophisticated dynamic traffic assignment model (DYNASMART) in order to also simulate the effects of ATIS, but the simulated information strategies are system-oriented and considered to not influencing the travellers' compliance, leading to unrealistic results.

In other models (for instance [10]) the compliance is confused with the ATIS' market penetration and the latest is considered to be depended on the trade-off between the expected time-saving and the access cost to information; the effect of information on equipped travellers is only modelled by considering a reduced stochastic dispersion in their route choices. The same is for the more advanced model in [11], where the stochastic approach of the previous papers is confronted with a dynamic flow-propagation approach, able to also take into account in a more realistic way the effects of queues. It is worth noting that market penetration and compliance to ATIS are two different things and that at least the latest should depend on the information accuracy.

To our knowledge, the first analyst that has pointed-out that ATIS cannot be used in order to reach system-optimum has been Halls ([12] and then [13]). In particular, in [13], even with a simplistic model, not applicable in general



conditions, Halls shows that: (a) ATIS do not allow for optimality; (b) information can only be delivered according to the users-optimum paradigm; (c) searching for a market penetration model is a false problem and the main use of ATIS is to stabilise the traffic system. We are substantially in accord with Halls and we complain that he has not received the due attention. Also in [14], where Yang and Huang accept the conjecture that information has to be supplied in accord to users-optimum, the misunderstanding of considering market penetration (not dependent on information accuracy), instead of an elastic compliance, leads to the false conjecture that a control tool (the price of ATIS services) can be able to move the traffic system to better performances. A similar error can be found in [15], where the inaccuracy of information is considered but it leads to stochastic dispersion of expected cost for different classes of travellers (non-equipped, equipped but not compliant, equipped and compliant) rather to non-compliance phenomena; the compliance (and the market penetration) is in fact assumed to be dependent on time-saving and not on information accuracy.

A quite different approach can be found in Mauro [16] and in De Florio [17] where the role of stabilisation of ATIS is recognised and the user-optimum validity is stated; the role of compliance is intrinsically treated, provided that the approach almost automatically ensure the consistency and the accuracy of the information. In fact, the approach proposed by the authors is to use ATIS as a "regulator" in proximity of the (stochastic) user equilibrium condition; it adjusts random diversions from equilibrium and the information is related to the steady state equilibrium (which is the target condition assumed to be maintained). It results that the information is accurate by definition (provided that the ATIS works). The limitation of the approach from Mauro and De Florio is that it can be applied only for systems in steady-state equilibrium and it is likely to work only for small random deviations. Moreover, it is assumed a closed-loop (with feedback) approach to the regulation problem, which implies that is needed a massive monitoring of the traffic and any deviation from the equilibrium conditions can be relieved and measured. Finally, if the cause of the deviation from the equilibrium conditions is not merely randomness, it is not ensured that the target conditions of the ATIS are compatible with the new changed traffic pattern, then it is no more ensured that information is accurate nor that the compliance is ensured.

2 The proposed model

The main characteristics of the proposed model consist in considering travellers' compliance to ATIS as to be elastic. Travellers update their compliance within a more general day-to-day dynamic process, where the compliance depends on the accuracy of the information supplied in previous days. For the sake of simplicity, travellers' choices are treated only with respect to route choices.

The model utilises a dynamic process approach similar to the one proposed by Cantarella and Cascetta [18]. Differently than what proposed by Cascetta et al. [19], the effect of ATIS is considered, for equipped travellers, to be on choice-upgrading, rather than on utility-upgrading: the compliance is updated

day-to-day and only the actual percentage of equipped and compliant travellers makes it choice according to the actual costs supplied by the ATIS. Non-equipped or non compliant travellers update their utility by averaging the utility of the previous day with the cost actually experimented in the previous day itself. In analytical terms:

$$\mathbf{F}^{t} = \alpha\left[\left(1-\delta^{t}\right)\cdot \boldsymbol{P}\left(\mathbf{V}^{t}\right)+\delta^{t}\cdot \boldsymbol{P}_{E}\left(\mathbf{V}_{E}^{t}\right)\right]\cdot \mathbf{d}+\left(1-\alpha\right)\cdot \mathbf{F}^{t-1} \tag{1}$$

$$\begin{aligned}\mathbf{V}^{t} &= \left(1-\beta\right)\cdot \mathbf{V}^{t-1}-\beta\cdot \mathbf{C}^{t-1}\\ \mathbf{C}^{t-1} &= \mathbf{A}^{T}\cdot \mathbf{c}^{t}=\mathbf{A}^{T}\cdot \boldsymbol{c}\left(\mathbf{f}^{t-1}\right)=\mathbf{A}^{T}\cdot \boldsymbol{c}\left(\mathbf{A}\cdot \mathbf{F}^{t-1}\right)\end{aligned} \tag{2}$$

$$\mathbf{V}_{E}^{t} = -\mathbf{C}_{E}^{t} \tag{3}$$

where

- t is the generic day of simulation of the dynamic day-to-day process;
- $\mathbf{F}^{t}$ is the path-flow vector (equipped + non equipped travellers);
- α is the percentage ([0,1]) of travellers that each day reconsider the possibility of choosing the path;
- δ^{t} is the percentage ([0,1]) of travellers that are both equipped and compliant to information at day t; $(1-\delta^{t})$ is the percentage of users that are not equipped or not compliant to information;
- $\mathbf{V}^{t}$ is the vector of systematic utilities, at day t, of the path-choice model for non-equipped and/or for equipped but non-compliant travellers;
- $\boldsymbol{P}()$ is the choice function (returns the path choice matrix) for non-equipped and/or non-compliant travellers; it is assumed to be based on the random utility theory, for instance via a Probit model;
- $\mathbf{V}^{t}_{E}$ is the vector of systematic utilities, at day t, of the path-choice model for equipped and compliant travellers;
- $\boldsymbol{P}_{E}()$ is the choice function for equipped and compliant travellers; it is based on the random-utility theory and the random dispersion is expected to be less than the one for non-equipped/non-compliant travellers;
- $\mathbf{d}$ is the vector of the total (equipped + non-equipped) O/D demand;
- β is the parameter (in the range [0,1]) of the utility-updating model that weights the travellers' experience and the travellers' expectancies;
- $\mathbf{c}^{t}$ is the link-cost vector actually experimented on the network at day t;
- $\boldsymbol{C}()$ is the path-costs computation function; provided a within-day-static model, the path cost vector can be computed as the sum of all components arc costs, via the $\mathbf{A}$ link-path incidence matrix;
- $\boldsymbol{c}()$ is the congestion model, that is the function that allows for link travel costs as a function of the actual link flows;
- $\mathbf{f}^{t}$ is the link-flow vector on the network at day t;
- $\mathbf{A}$ is the (within-day-static) flow propagation model, which allows for the link
- $\mathbf{F}^{t}$ flows as a function of path flows;
- $\mathbf{C}^{t}_{E}$ is the path-costs vector suggested by the ATIS at day t.

Eqn. (1) formalises the path-choice updating model for the dynamic process; it is assumed that only a part (α) of the total demand reconsider day-to-day the

path-choices, while the rest merely confirms the path choices pattern of the previous day ($\mathbf{F}^{t-1}$); in turn, only a percentage (δ^t) of the "reconsidering demand" actually uses, at day t, the information supplied by the ATIS, this accounts for the travellers that are both equipped and compliant with the information. The path choice models for non-equipped and/or non compliant travellers can be different (typically less deterministic). Non equipped and/or non compliant travellers behave according to an utility updating model expressed by eqn. (2) which is based on a classical learning process. Equipped and compliant travellers behave according to the path costs supplied by the ATIS, as shown by eqn. (3).

A crucial characteristic of the proposed model is to consider the compliance (δ^t) dependent on the simulation day (t) as a function of the accuracy of the information supplied by the ATIS in previous days. To this aim, the following compliance-updating models is used within the general dynamic process:

$$\delta^t = (1-\mu)\cdot\delta^{t-1} + \mu\cdot\delta_{max}\cdot exp\left(\chi\frac{\left\|\mathbf{C}_E^{t-1} - \mathbf{C}^{t-1}\right\|}{\left\|\mathbf{C}^{t-1}\right\|}\right) \tag{4}$$

where

μ is a parameter (in the range [0,1]) of the compliance updating model, it accounts for propensity to update the compliance from one day to the other, the greater is μ, the more dynamic is the updating process;

δ_{max} is the maxim allowed compliance ([0,1]), it measures the market penetration of the ATIS, that is the percentage of equipped travellers;

χ is a parameter (<0) that accounts for the sensitivity of the travellers to the fault of the ATIS in suggesting the accurate actual path costs.

Eqn. (4) states that the compliance of the equipped travellers depends on the distance between the path costs supplied by the ATIS and the path costs actually experimented by travellers. Perfectly accurate information ($\mathbf{C}_E^t \equiv \mathbf{C}^t$) give rise to maximum increasing of compliance and, if maintained over days, leads to the maximum allowed compliance (δ_{max}), while the larger is the discrepancy of the supplied information the stepper the decreasing of the compliance.

3 Application of the model

The proposed model has been numerically tested on a simple two-link network, as depicted in the following figure.

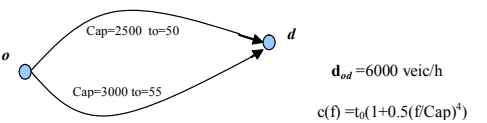


Figure 1: The two-link test network.

The model has been tested in accordance to two different information strategies.

The first one, denoted as I1, consists in supplying (via ATIS) all days the same information, that is the path costs that were established if a (stochastic) user-equilibrium were reached by the system; for such an information strategy three sub-cases will be considered: (a) the compliance is considered to be rigid at the value 0.6 of the market penetration (δ_{max}); (b) the compliance is considered to be elastic up the value of market penetration of 0.6; (c) the compliance is considered to be elastic up to the value of market penetration 0.7.

The second information strategy (I2) consists in supplying an accurate information, so that the ATIS is able (which is not trivial) to estimate path costs that match the path costs that will be actually experimented on the network; this ensures that the compliance is the maximum allowed and the elastic compliance model is able to internally simulate such a phenomenon. In case of accurate information strategy two sub-cases are tested: (a) the market penetration is 0.6 and (b) the market penetration is 0.3.

In all cases, the parameters of the choice-updating and of the utility-updating models are α= 0.5 and β=0.6.

The results for the I1 information strategy are shown in the following three figures. In all figures the dark line represents the system dynamics without ATIS, while the thin line refers to the presence of ATIS. Note that in sub-cases a and b the system does not reach a stable configuration. In sub-case a (rigid compliance) the presence of ATIS seems to reduce system's oscillations with respect to the absence of ATIS in a more effective way than in sub-case b; however, sub-case a is unrealistic, provided that compliance is erroneously considered to be constant. In the figure related to sub-cases b and c also the dynamics of the compliance is depicted. In sub-case c the system is able (due to the higher value of the ATIS market penetration) to reach stability and the compliance's dynamics shows that the higher market penetration enables the whole system to self-correct the effects of the inaccurate information strategy.

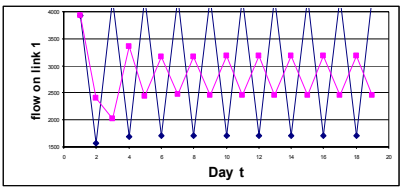


Figure 2: Experiment I1.a.

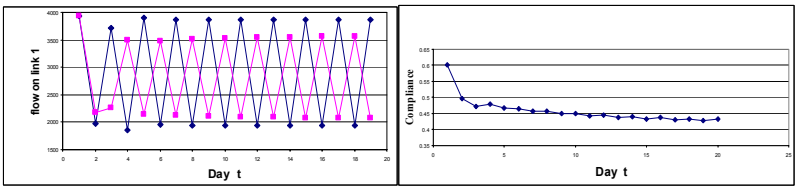


Figure 3: Experiment I1.b.

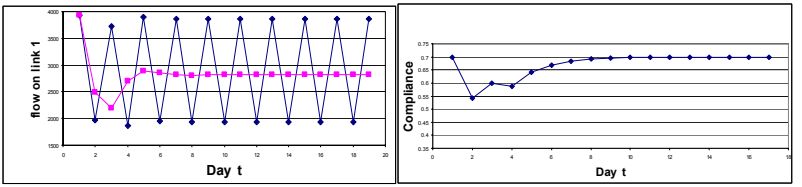


Figure 4: Experiment I1.c.

The results of the accurate information strategy (I2) are described in the following figure. Both in sub-case a and b the system dynamics became stable and, due to the intrinsic better performances of the accurate information strategy, this happens both for an high and a low level of market penetration. Obviously, the lower the market penetration the slower is the stabilisation.

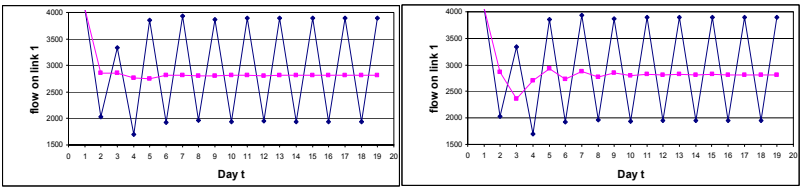


Figure 5: Experiment I2.a and I2.b.

The previous numerical results have induced a more general and theoretical investigation of the system dynamics stability in presence of ATIS. The stability of the process has been investigated with reference to local properties, provided that the theoretical investigation of global stability is not suitable in general cases.

It can be proven that the Jacobian matrix of the dynamic process, computed at the equilibrium point where the local stability is investigated, in case of elastic compliance and accurate information strategy, can be written as:

$$\begin{bmatrix} (1-\beta)\cdot\mathbf{I} & \beta\cdot\mathbf{J}_c \\ (1-\alpha\cdot\delta_{max}\cdot\mathbf{J}_f^E\cdot\mathbf{J}_c)\cdot\alpha\cdot(1-\beta)\cdot(1-\delta_{max})\cdot\mathbf{J}_f & (1-\alpha\cdot\delta_{max}\cdot\mathbf{J}_f^E\cdot\mathbf{J}_c)^{-1}\cdot[(1-\alpha)\cdot\mathbf{I}+\alpha\cdot\beta\cdot(1-\delta_{max})\cdot\mathbf{J}_f\cdot\mathbf{J}_c] \end{bmatrix} \quad (5)$$

where

$\mathbf{J}^E_f$ is the jacobian of the path-choice + flow propagation model for the equipped travellers;

$\mathbf{J}_f$ is the jacobian of the path-choice + flow propagation model for the non-equipped travellers;

$\mathbf{J}_c$ is the jacobian of the congestion model (link-cost functions);

$\mathbf{I}$ is the identity matrix.

Previous eqn. (5) is the generalisation to the proposed model of the jacobian matrix of the dynamic process stated by Cantarella and Cascetta [18]. With the further simplifying assumption of neglecting the different stochasticity in the path-choice model of the non-equipped/non-compliant and equipped/compliant travellers ($\mathbf{J}^{E}_{f}= \mathbf{J}_{f}$), the eigenvalues ($\lambda$) of the matrix in (5) can be related to the eingenvalues (γ) of the matrix ($\mathbf{G}= \mathbf{J}_{f}\,\mathbf{J}_{c}$) via the following equation:

$$\alpha\cdot\beta\cdot\gamma_{k}\cdot(1-\delta_{max})\cdot\lambda=\lambda\cdot[\lambda-(1-\beta)]\cdot[1-\alpha\cdot\delta_{max}\cdot\gamma_{k}]-[\lambda-(1-\beta)]\cdot(1-\alpha) \quad (6)$$

In other terms, for any given value of γ_k, eqn. (6) allow to compute a couple of values λ. The following figure, for given values of α ad β (α=0.5 and β=0.6) shows the regions of the complex plane (ellipses parametric with respect to d_{max}) to which eigenvalues g must belong in order to ensure that eigenvalues λ belong to a circle (in the complex plane) of radius 1. Thus, the following figure shows the local stability regions of the dynamic process.

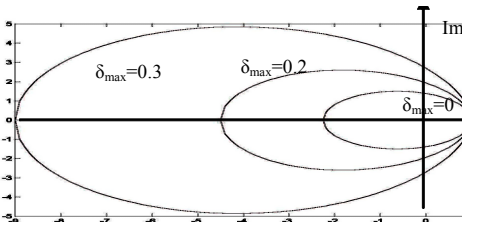


Figure 6: Stability region.

This shows that, in case of accurate information strategies and in case of a correct simulation model, which explicitly simulate compliance elasticity with respect to information accuracy, the stability region of the equilibrium condition of the dynamic process monotonically increases with increasing market penetration. This is a desired result for ATIS applications and contradict some common results that, incorrectly, to our opinion, show instability phenomena in case of increasing ATIS market penetration. Such a not negligible difference is due, to our opinion, to the lack of other models to explicitly simulate compliance to information and to the fact that most of the previous models does not deal with accurate information.

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