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A joint model of travel information acquisition and response to received messages

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ABSTRACT

This paper presents a discrete-choice model of traveler response to information. It contributes to existing approaches by describing both the acquisition *and* the effect on travel choices of a variety of travel information types using a single integrative and parsimonious discrete-choice model. By doing so, the model captures the notion that both types of decisions (to acquire information and to execute a travel alternative) are the result of a single underlying system of preferences and beliefs. The model was estimated on choice sequences observed in a multimodal travel simulator experiment with information provision. Estimation results show a good model fit, and parameter estimates have intuitive interpretations.

1. Introduction

Understanding traveler response to information has become one of the most important challenges for the travel behavior research community (e.g. Ettema and Timmermans, 2006; Gao et al., 2010). One of the more popular approaches for helping gain this understanding appears to be the paradigm of discrete choice modeling. Notwithstanding the valuable insights provided by the application of discrete choice theory to understand response to information, this body of literature faces an important limitation: almost without exception the focus has been either on travelers' decisions to acquire (or pay for) information (e.g., Polak and Jones, 1993; Khattak et al., 2003; Molin and Timmermans, 2006; Molin et al., 2009) *or* on the effect of provided information on subsequent travel choices (e.g., Adler and McNally, 1994; Bogers et al., 2005; Tsirimpa et al., 2007; Chorus et al., 2009; Ben-Elia and Shiftan, 2010).

The few studies that did treat information acquisition and the effect of information *in combination* did not take into account the response within one integrative discrete-choice model. Specifically, Emmerink et al. (1996) estimated a series of separate discrete-choice models of listening propensity to travel-time-related radio traffic information and the influence of the information on route choice, based on a revealed-preference dataset. Polydoropoulou and Ben-Akiva (1998) used a combined revealed-preference/stated-preference dataset to estimate a series of separate discrete-choice models of user adoption of and willingness to pay for travel-time-related information services, including the effect of received information on switching behavior. Hato et al. (1999), also using a combined revealed-preference/stated-preference dataset, estimated a discrete-choice model of acquisition of time- and distance-related information. Subsequently, the estimation results were used in the process of estimating a route-choice model that takes information use into account.

We feel that since response to information is likely to involve *sequences* of (possibly multiple) information acquisition steps followed by a travel choice, capturing the sequential nature of traveler response to information in empirical studies

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is important. The reason that this is important is that decisions to acquire travel information and to execute a travel alternative are highly interrelated as they are driven by the same preferences and beliefs. Take for example a traveler that has a high intrinsic dislike for transit and a high value of time. This traveler will have a limited inclination to choose a transit alternative, especially when she believes it to be slow. Crucially, her preferences also imply that she will have a limited inclination to acquire information about transit fares, and a somewhat larger (given her high value of time) but still limited inclination to acquire information about transit travel times. In the unlikely case that the traveler does acquire some form of transit information, the received information is unlikely to make her change her mind towards choosing transit, because she intrinsically dislikes that mode of travel. However, suppose now that on a given day the traveler believes that available car options are very slow (e.g. because she heard about the occurrence of an incident). In this new situation, the traveler (given her high value of time) will not only be more inclined to choose the transit option, but her inclination to acquire transit information increases as well. Furthermore, when received information is favorable to transit, she is relatively likely to choose transit for the given trip. This example illustrates how travelers' response to travel information consists of a sequence of highly interrelated decisions (concerning information acquisition and travel). Choice models that do not integrate these two dimensions of choice ignore the important notion that they are both driven by the same set of preferences and beliefs. Therefore, such models may generate suboptimal insights concerning traveler response to information.

From a modeler's perspective, there is yet another reason to integrate in one model choices to acquire information and to execute a travel alternative: given that both types of choices are driven by a generic set of preferences, observed information acquisition and travel choice patterns can be used jointly to estimate preferences such as (dis-)likes for travel modes and travelers' travel time valuations. Such a joint estimation is not only behaviorally intuitive but also econometrically pragmatic.

This paper presents and estimates a discrete-choice model of travelers' sequential responses to information. In contrast with earlier work discussed above our model can be used to simultaneously estimate both information acquisition steps and the effect of messages received on subsequent travel choices. The estimation of the model was based on travel simulator choice data from a stated-preference experiment. Choice data were collected on travelers' responses to a personal intelligent travel assistant, which provided a variety of pre- and in-trip information options in a multimodal setting. The collected choice data contained sequences of (possibly dozens of) information acquisition steps followed by a travel choice.

The work presented here is related to work presented in a previous paper (Chorus et al., 2010) that proposed, at the conceptual level, a search-theoretic quantification of the value of travel information. Here we build on the ideas presented in that paper to provide a formal, discrete-choice-based account of sequences of information acquisition steps followed by a travel choice. There is also a relation between this paper and Gao et al. (2011). That paper builds on the models presented here, in order to derive a latent class model of information acquisition and traveler response. Gao et al.'s analyses differ from the ones presented here in the following ways: (i) their paper focuses on travel time information for a set of known routes, whereas our paper focuses on a range of information types for known and unknown routes; (ii) whereas their models are estimated based on observed route choices only, our model uses route choices and information acquisition choices jointly for model estimation; (iii) Gao et al.'s empirical analyses are based on a synthetic dataset, whereas our paper uses data collected in a travel simulator experiment.

In a more general sense, this paper builds on the large and growing body of literature concerning the development and testing of discrete choice models of traveler response to information. This body emerged in the late 1980s, when technological advances in the gathering and synthesizing of transportation data and the presentation of information to travelers started to trigger visions of increasing capabilities of travel information services, along with an increasingly important role for such services in traveler decision making (e.g. Boyce, 1988; Arnott et al., 1991; Ben-Akiva et al., 1991; Mahmassani and Jayakrishnan, 1991; Polak and Jones, 1993). These visions gradually led to the introduction of the acronym ATIS for Advanced Traveler Information Services (e.g. Khattak et al., 1993; Schofer et al., 1993; Adler and McNally, 1994). ATIS started out as systems that, based on observations of the current situation in the transport network in combination with historic data, provided car-drivers with travel time estimates, advice or route guidance, and transit-riders with up-to-date messages on delays of trains or buses. The information was provided to travelers through radio, variable message signs, telephone services and, starting in the mid-1990s, internet-sites. Over the years, these ATIS have become increasingly capable of providing travelers with reliable and relevant information, in times when the negative externalities of passenger transport, in terms of e.g. congestion, inaccessibility of urban areas, safety issues, utilization of fossil resources and environmental pollution, have become increasingly relevant.

These two factors in combination (increasing ATIS capabilities and increasing passenger transport externalities) generated substantial interest among transportation academics regarding traveler response to information, or the behavioral aspects of travel information. This interest mainly concerned one of two lines of thought: firstly, there is what can be called a *marketing* point of view (e.g. Abdel-Aty et al., 1996, Abdel-Aty, 2001; Polydoropoulou et al., 1997; Khattak et al., 2003; Molin and Timmermans, 2006; Molin et al., 2009) which is predominantly concerned with the potential of ATIS as a business case, either stand alone or as part of an effort to gain or retain customers for some transportation service, e.g. urban transit. A second and perhaps more dominant line of thought focused on ATIS as a potential tool for Travel Demand Management (TDM). This TDM or *transport policy* point of view (e.g. van Berkum and van der Mede, 1993; Adler and McNally, 1994; Emmerink et al., 1995, 1996; Hato et al., 1999; Kenyon and Lyons, 2003; Jou et al., 2005; Chorus et al., 2009) investigates the high expectations of travel information provision as a means to change traveler behavior in ways that are deemed beneficial to the transport system. Examples of such behavioral changes are a modal shift from car to transit and a more efficient use of the available road capacity due to route and departure time choice adaptations.

As stated above, the contribution of this paper to this literature on modeling traveler response to information lies in jointly taking into account the acquisition of information by travelers and their response to received messages. Our model is estimated on data obtained by means of a travel simulator-experiment; please see further below (Section 2) for a brief overview of other studies concerning traveler response to information which use travel simulator data for model estimation.

The rest of this paper is organized as follows: data collection is presented in Section 2. The specification of the formal model is presented in Section 3. The estimation of the model and results are presented in Section 4; Section 5 draws conclusions.

2. Data collection: a stated-preference travel simulator experiment

This section presents the collection of a dataset tailored to the empirical estimation of a discrete-choice model of travelers' sequential responses to information. It should be borne in mind that our model was developed to cover a wider range of travel alternatives and information acquisition options than the ones that are present in our dataset. Nonetheless, the collected dataset forms a good example of the type of choices we wish to model.

2.1. A multimodal travel simulator with information provision

The constructed simulator studies decision making when the knowledge of multimodal networks is incomplete and in the presence of highly functional travel information services that are currently not yet available in real-world travel choice situations. It stands in a long tradition of computer-based travel simulator tools of varying levels of sophistication (e.g. Adler et al., 1993; Chen and Mahmassani, 1993; Adler and McNally, 1994; Koutsopoulos et al., 1994; Walker and Ben-Akiva, 1996; Mahmassani and Liu, 1999; Katsikopoulos et al., 2002; Bonsall and Palmer, 2004; Sun, 2009; Ben-Elia and Shiftan, 2010). See Chorus et al. (2007) for a more detailed discussion of the simulator and a validation effort. Participants to our simulator-experiment were faced with a computer screen that consists of four parts, containing a transport network, an information service, a visual aid and a trip context respectively. See Fig. 1 for a screen shot.

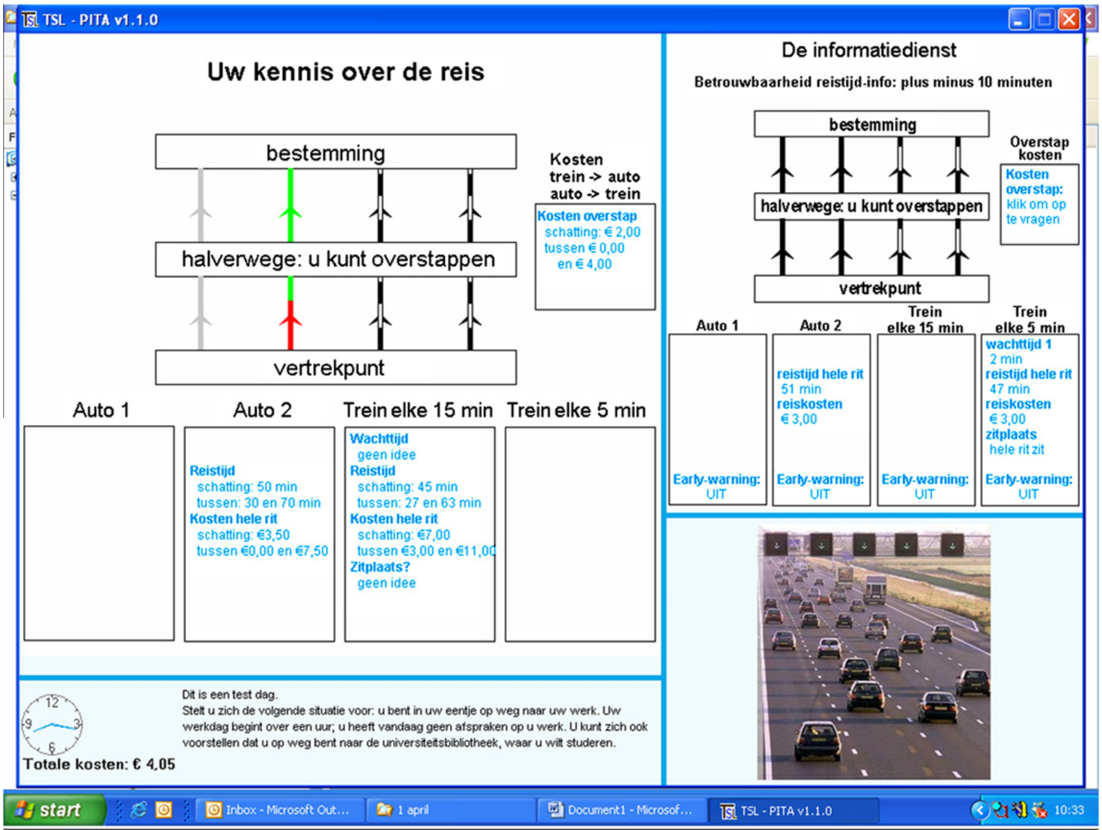

Fig. 1. Screenshot of the simulator (in Dutch).

The transport network consisted of a hypothetical O–D pair, connected by four paths displayed as arrows. Two arrows symbolize two car options, i.e., highway routes. The two routes may differ in terms of travel times and costs. Next to these two car options are two intercity train options which may differ in travel time and costs as well as seat availability. The number of a priori options "known" to the traveler is randomly generated and varies per trip. "Unknown" options are inactive and cannot be used by the traveler. A priori knowledge provided to the traveler for the "known" options consists of the following: for car and train options, *best guesses* for travel times and travel costs are provided, as well as *certainty intervals*, i.e., ranges of time and costs within which the participants are told (correctly) that actual values will almost certainly fall. Train travelers do not know the exact departure times a priori, nor do they know whether or not a seat will be available.

Upon choosing an alternative, the traveler is told the actual travel time and cost of the chosen alternative; train travelers are also told whether or not they would have a seat. As the trip commences, the clock starts ticking 1 s of simulator time per 1 min of travel time. The actual travel time and travel costs were drawn from a normal distribution with best guesses as means and a quarter of the length of the certainty intervals as standard deviations, so that 95% of the actual values fall within the certainty interval. Seat availability was randomly drawn from a discrete distribution (50% chance of having a seat), and waiting times were drawn from a uniform distribution between 0 and the headway (5 or 15 min).

The layout of the information service is a copy of the transport network. All the information provided in the sample used for this analysis was fully reliable, meaning that every message received corresponded to the actual value of that particular attribute. Participants were informed of this complete reliability. A large number of information acquisition options is available and can be categorized into three types: (1) type *A* for "alternative assessment" (acquiring estimates of one or more attributes of one of the known alternatives); (2) type *G* for "generation of alternatives" (adding a formerly unknown mode and route combination to the traveler's choice set); and (3) type *W* for "warning" (asking for the provision of early warnings for selected travel alternatives with very long travel times). See Section 3.3 for a more detailed and formal account of the content of these different information types.

Assessment information price is listed for every attribute and varies between 0.15, 0.30, and 0.45 Euros. *Generating* information price varies between 0.45, 0.60 and 0.75 Euros. After the purchase of this type of information is confirmed, the alternative is made active and estimates for all the alternative's characteristics are provided. *Warning* information costs 0.30, 0.45 or 0.60 Euros. Once the early warning function is activated, it operates for every alternative; a warning is issued whenever an alternative is about to be chosen with a much longer travel time than the reported best guess travel time. Note that all information costs were prespecified, and did not vary as a function of user characteristics (e.g., sociodemographic factors) nor as a function of past information acquisition patterns. Also note that the ranges of the information costs-attribute were specified to be realistic in the context of the real-world travel information costs prevailing in the Netherlands at the time of the experiment.

Table 1
Response group characteristics ($N = 31$).

Variable	Frequency
Gender	
Female	14
Male	17
Age	
<25	16
25–39	10
40–65	5
Completed education	
Primary education	0
Secondary school	21
Higher education	10
Main out-of-home activity	
Paid work	9
Education	18
Other	4
Driver's license	
Yes	27
No[a]	4
Car availability	
Always/usually	11
Sometimes	14
Less than sometimes	6
Public Transport (PT) season ticket	
Some form of	24
None	7

[a] Note that drivers without a license might still choose to travel by car if a family member could drive.

2.2. The experiment

Participants were recruited by placing advertisements in a campus newspaper and another free newspaper. An email was also sent out to approximately 500 students. The experiment took 2 h, and a 20 Euro reward was offered for participation. Participants were required to have some experience with both car and train travel. Two hundred sixty-four individuals were recruited, of which 31 were randomly assigned to the experimental conditions on which we focus here (i.e., fully reliable information conditions). Table 1 shows the characteristics of the socio-economically rather heterogeneous response group.

After a short introduction, participants made two test rides. Subsequently, a number of trips (at most 25) were made using the information services. In total, the 31 participants made 559 trips (excluding test trips), equaling about 18 trips per participant on average. Some 30% of the trips were designated as important business trips under "trip purpose". At the start, the travel choice set contained 2.37 alternatives on average (the minimum (maximum) was set at one (four)), and the information choice set contained 21.93 information options. More specifically, 1 early warning option, 1.63 options for generating alternatives and 19.30 assessment options for known alternatives were available on average per trip at the outset. Note that this last number reflects that travelers could acquire information for more than one attribute at one time, and that each was considered a separate information alternative. In total, 931 pre-trip information acquisition steps were recorded (equaling an average of 1.67 pre-trip information acquisition steps per trip, with an observed maximum of 7 information acquisition steps). See Table 2 for summary statistics.

Table 2
Choice frequencies for information acquisition and travel choices.

Choice alternative	# Times available at starting situation	Freq. (N = 1490 decision stages)
Information acquisition choice set		
Activate early warning function	559	91
Generate car 1	192	55
Generate car 2	169	58
Generate train 1	204	94
Generate train 2	364	162
Assess car 1 travel time	367	53
Assess car 1 travel costs	367	46
Assess car 1 travel time, travel costs	367	28
Assess car 2 travel time	390	65
Assess car 2 travel costs	390	39
Assess car 2 travel time, travel costs	390	25
Assess train 1 travel time	355	30
Assess train 1 travel costs	355	48
Assess train 1 waiting time	355	13
Assess train 1 seat availability	355	4
Assess train 1 travel time, travel costs	355	11
Assess train 1 travel time, waiting time	355	21
Assess train 1 travel time, seat availability	355	0
Assess train 1 travel costs, waiting time	355	1
Assess train 1 travel costs, seat availability	355	1
Assess train 1 waiting time, seat availability	355	0
Assess train 1 travel time, travel costs, waiting time	355	4
Assess train 1 travel time, travel costs, seat availability	355	2
Assess train 1 travel time, waiting time, seat availability	355	4
Assess train 1 travel costs, waiting time, seat availability	355	0
Assess train 1 travel time, travel costs, waiting time, seat availability	355	14
Assess train 2 travel time	213	9
Assess train 2 travel costs	213	26
Assess train 2 waiting time	213	5
Assess train 2 seat availability	213	2
Assess train 2 travel time, travel costs	213	5
Assess train 2 travel time, waiting time	213	6
Assess train 2 travel time, seat availability	213	0
Assess train 2 travel costs, waiting time	213	0
Assess train 2 travel costs, seat availability	213	0
Assess train 2 waiting time, seat availability	213	0
Assess train 2 travel time, travel costs, waiting time	213	3
Assess train 2 travel time, travel costs, seat availability	213	0
Assess train 2 travel time, waiting time, seat availability	213	0
Assess train 2 travel costs, waiting time, seat availability	213	0
Assess train 2 travel time, travel costs, waiting time, seat availability	213	6
Travel choice set		
Execute car 1	367	136
Execute car 2	390	123
Execute train 1	355	199
Execute train 2	213	101

Altogether, this means that 931 information acquisition steps plus 559 travel choices totaling 1490 decision steps were observed. The early warning function was activated in 16.3% of the observed trips. In 7.6% of the cases, an unknown car option and in 17.2% an unknown train option was generated. This is consistent with the fact that on average, more car-options than train-options were available to the traveler (see directly above). Also, 17.2% of the observed decision steps consisted of some form of assessment of known car options, while 14.4% consisted of some form of assessment of known train options. In 37.5% of the observed actions, no information was acquired and a travel alternative was directly chosen from the travel choice set. In 17.4% of the cases, a car option was executed immediately, as was a train option in 20.1% of the observations. See the Appendix for a description of an observed sequence of information acquisition followed by a travel choice for an arbitrary trip.

At this point it is important to mention that there is a continuing debate about the external validity of data collected by means of the type of simulator experiments as presented above. More specifically, various authors have raised the question whether (or: to what extent) such data may be considered representative of real life choices made by actual travelers. This question has been addressed in a number of critical reviews and empirical validation studies. Notable contributions to this literature include Koutsopoulos et al. (1995), Bonsall et al. (1997), Mahmassani and Jou (2000), Bonsall (2004), and Mahmassani (2006). Although it would go beyond the scope of this paper to provide an in-depth discussion of the findings of these studies, it appears that the authors agree that properly designed travel simulator experiments are able to deliver data that have a reasonable degree of external validity. Concerning the particular travel simulator experiment that forms the basis of our datacollection effort, a separate validation has been performed (Chorus et al., 2007). That study used a variety of analysis methods to test face and external validity of the simulator data. It also compared data collected in the experiment with data concerning real life choices made by the same participants, and based on these analyses it is in the end concluded that the simulator "appears to offer a means to generate valid data concerning multimodal travel behavior under conditions of knowledge limitations, in the presence of several types of advanced information services." Notwithstanding this rather positive outcome of the validation effort, we wish to stress that no definite answers regarding the validity of data obtained in this and other simulator experiments are available. As such, we would like to emphasize that results and conclusions presented further below should be treated with care, especially when transferring them to other (real life) situations.

3. A formal model of traveler response to information

In this section we shall present a formal representation of our model of traveler response to information. We shall represent both travelers' pre-trip information acquisition choices as well as the effect of acquired pre-trip information on their travel choices. In developing the model, we refer to the data available from the travel simulator experiment described above.

3.1. Conceptualisations

Consider a traveler who faces a choice situation that consists of a number of mode and route options, not all of which are necessarily known at the outset. Furthermore, the attributes of the known alternatives (such as travel times and travel costs) are uncertain although the traveler may have an idea of their distributions, for example in terms of means and variability. The traveler can either directly choose one of the known mode and route combinations based on his or her existing knowledge or decide to purchase one of the many available information bits. If the traveler opts to acquire information, when it is received he or she again faces the choice of executing one of the known travel alternatives (based on his or her initial knowledge *and* the received information) or acquiring additional information. Each pre-trip choice situation may therefore consist of a sequence of decisions involving a number of information acquisition steps (possibly none), followed by a travel choice.

Fig. 2 provides a depiction of the structure of our model of traveler response to information. We will discuss this structure by going through the figure, following the arrows in alphabetical order. When a traveler considers making a trip (a moment we denote as "decision step 1"), he or she is assumed to have prior knowledge of a set of known travel alternatives. The attributes of known alternatives are known only to a limited extent. For example, the travel times of known car and public transit options are uncertain, as are waiting time and seat availability in public transit.

The traveler now faces a decision: either to immediately choose one of the known travel alternatives (arrow $\mathbf{A_1}$ – the subscript refers to the decision step) or to acquire some form of information first ($\mathbf{B_1}$). We model the traveler's decision by postulating that he or she chooses from a choice set that contains all known travel alternatives plus all known information acquisition options. The traveler's choice from this set is driven by utility maximization: he or she compares all known travel alternatives and information acquisition options and chooses the one with the highest utility. The utility of a travel alternative is a linear additive function of best guesses and uncertainty measures associated with the different attributes of the alternative. The utility of an information acquisition option is conceptualized as the utility the traveler anticipates to derive from the anticipated set of travel alternatives after the information is received.

For example, the utility of acquiring a travel-time estimate for one of the known travel alternatives equals the anticipated utility of choosing from the known travel alternatives after receiving the estimate. Given our focus on fully reliable information, we assume that travelers anticipate that they will completely replace their prior travel-time knowledge with received information. For example, a traveler who initially believes that the travel time for one of the known travel alternatives will lie somewhere between 25 and 35 min knows that acquiring travel-time information will replace this range with a crisp attribute value equaling the received travel-time estimate (e.g., 31 min). We assume that receiving information about one

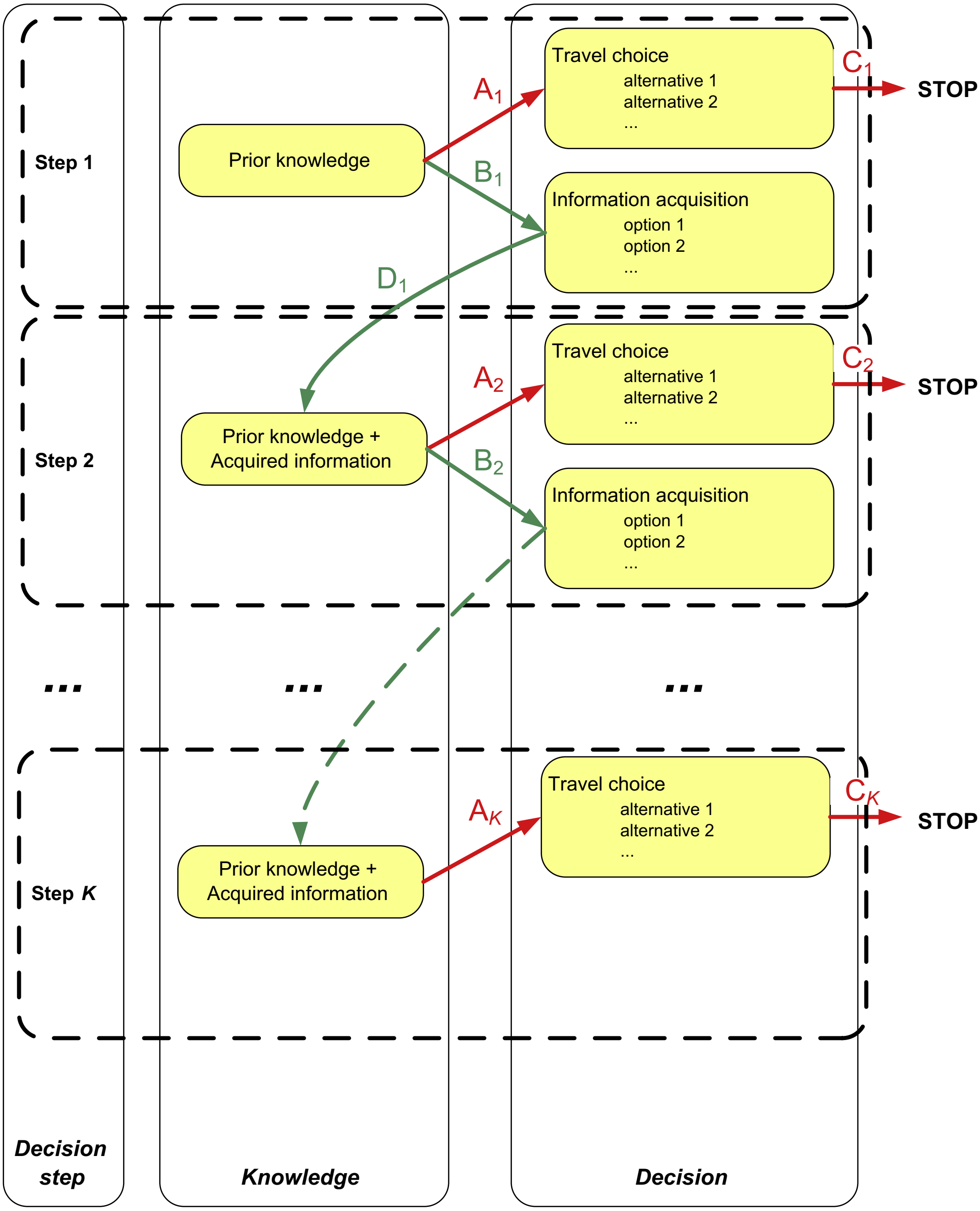

Fig. 2. Visualization of the structure of the model.

uncertain attribute (e.g., travel time) does not impact a traveler's perception of other uncertain attributes (e.g., travel costs). If the maximum utility alternative is a travel alternative, the trip begins and the travel alternative (i.e., a particular mode and route combination) is executed ($\mathbf{C_1}$). The traveler may at some point decide to acquire in-trip information and possibly change routes or travel modes while underway, thus beginning the process anew. Although in this paper we focus on pre-trip response to information, our model can be extended to cover in-trip response as well.

If the maximum utility alternative for the set of travel alternatives and information acquisition options is an information acquisition option, the information is acquired and a message is received from the information service. This message may take on different forms, depending on the type of information that is acquired. The received information increases the traveler's knowledge base ($\mathbf{D_1}$). For example, the information may alter his or her perceptions of the attributes of known alternatives (e.g., when travel-time information is acquired), or it may result in adding a new mode and route combination to the set of travel alternatives.

After acquiring the information, the traveler "moves" to decision step 2 and faces a decision similar to the one in decision step 1: he or she may either decide to choose one of the known travel alternatives ($\mathbf{A_2}$) or acquire additional information first ($\mathbf{B_2}$). Note again that this decision step, as well as all other decision steps discussed in this paper, is a pre-trip decision moment. There are two changes compared to the choice situation at decision step 1: firstly, the traveler's knowledge base has increased since decision step 1. For example, a previously uncertain travel time of one of the known mode and route combinations (reflected by a best guess and a measure of uncertainty) may have been replaced by a crisp attribute value. Secondly, the set of information acquisition options has become smaller: we assume that once a particular bit of information is acquired (e.g., a travel-time estimate for one of the known travel alternatives), it cannot be acquired again. In practice, as well as in our choice experiment, a large number of information acquisition options of the three types considered remains (such as acquiring travel-time information for another of the known travel alternatives). This iterative process of information acquisition may go on and on, and only stops when the traveler decides to choose one of the known travel alternatives (based on his or her knowledge at that point in time), or when all $\boldsymbol{K}$ available information pieces have been acquired.

We conclude our discussion of the model's structure and main underlying assumptions by adopting the perspective of the analyst. In the tradition of discrete-choice modeling, we assume that the analyst is unable to faultlessly observe the utility a traveler derives from choosing particular travel alternatives or information acquisition options. We model this by adding random components to the utility of travel alternatives and information acquisition options. In addition to independent and identically distributed (i.i.d.) extreme-value Type I errors, we use normally distributed agent effects to reflect a traveler's intrinsic preferences for particular travel alternatives (e.g., a preference for car over train travel) and information acquisition options (e.g., a preference for assessing known travel alternatives over generating unknown ones). Compared to conventional travel choice models, our model of traveler response to information has one special feature in terms of random-utility components. We assume that the random utility associated with a travel alternative also enters the utility function of relevant information acquisition options. This follows directly from our specification of information utility in terms of the utility of the anticipated travel choice set after the information is received. This utility refers not only to observed, but also to unobserved utility. In other words, we assume that unobserved, intrinsic preferences for particular travel alternatives echo through in travelers' preferences for relevant information acquisition options. Consequently, our model can, for example, capture the intuitive notion of a traveler who harbors a great unobserved dislike of public transit and as a result is very unlikely to acquire public transit information.

3.2. Notation and basic derivations

Let us denote individuals as n, trips as t and decision steps as d. Note that the notion of a decision step is virtual: it is used here to describe the sequential nature of choices made by an individual within one and the same pre-trip situation. For example, an individual who first decides to assess the travel time of a train option and then decides to generate and subsequently choose a new train option has reached three decision steps d (two information acquisition steps and one travel choice) in the context of one trip t. As such, the time-scale for decision steps is generally one of seconds or minutes. Although theoretically, the number of decision steps may become very large, in practice one would expect that the number of steps will be rather small, involving possibly about a handful of information acquisitions. We here focus on the situation where a traveler acquires information shortly before embarking on the trip, although the model has relevance for longer planning horizons as well. Every trip t begins with a starting situation S_t. At any decision step d of trip t, the individual has the opportunity to choose to acquire a piece of information, denoted as $I_{ntd} = r$, from the set of information options available at that moment, C^I_{ntd}. Let us denote the total number of decision steps used to acquire information as D_{nt}. If information has been acquired at step d, the individual proceeds to step $d + 1$ of trip t. If, instead of acquiring information, a travel alternative is chosen from the set of available travel options, $T_{ntd} = i, i \in C^T_{ntd}$, the trip is executed and the individual proceeds to step $d = 1$ of trip $t + 1$. The total choice set faced by individual n at step d of trip t consists of both travel alternatives and information options: $C_{ntd} = \{C^T_{ntd}, C^I_{ntd}\}$. Thus, for every trip there is a sequence of a number of information acquisition steps followed by a travel choice. Let us denote this sequence in general as $[\{I_{ntd}, d = 1, 2, \ldots, D_{nt}\}, T_{ntD_{nt}+1}]$. See Fig. 3 for a visualization of such a sequence, including relevant notation.

The way n, d and t of the choice sets are indexed reflects their conditionality with respect to the information acquired by the individual earlier in the trip. This conditionality works as follows: every piece of information can only be acquired once, so a piece of information acquired at step d is no longer an element of the choice set of information options at step $d + 1$. Furthermore, the individual can acquire information by generating a previously unknown travel alternative. The acquisition of such information at step d adds a travel alternative to the choice set of travel alternatives at step $d + 1$. A second source of conditionality stems from the assumption that information received about one or more of the attributes of known alternatives will alter the individual's perception of these attributes. This will be discussed in more detail below. When writing the probability of observing a particular sequence of information acquisition steps followed by a travel choice, $[\{I_{ntd}, d = 1, 2, \ldots, D_{nt}\}, T_{ntD_{nt}+1}]$, conditionality is reflected by formulating this probability as a series of conditional probabilities:

$$P([\{I_{ntd}, d = 1, 2, \ldots, D_{nt}\}, T_{nt}]) = P(I_{nt1}|S_t) \cdot P(I_{nt2}|I_{nt1}, S_t) \cdot \cdots \cdot P(T_{ntD_{nt}+1}|I_{ntD_{nt}}, \ldots, I_{nt2}, I_{nt1}, S_t). \quad (1)$$

In order to estimate an integrated model of information acquisition and mode and route choice based on the observed sequences, we need to write the probabilities of travel alternatives and information acquisition options on the right-hand side of Eq. (1) in terms of their respective utilities. Section 3.3 provides the specification for the utility of the travel alterna-

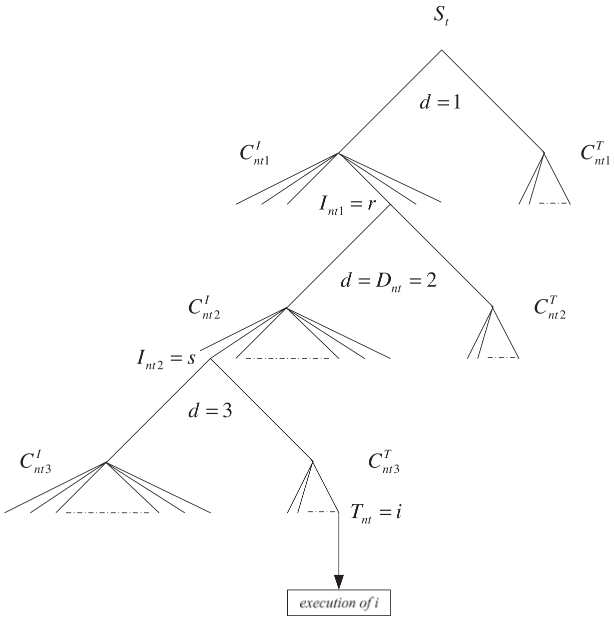

Fig. 3. Depiction of sequence $[\{I_{nt1}=r, I_{nt2}=s,\}, T_{nt3}=i]$.

tives, and Section 3.4 provides the specification for the utility of the information acquisition options. The resulting choice probabilities and log likelihood are derived in Section 3.5.

3.3. Utility specification of travel alternatives

Eq. (2) specifies the utility perceived by individual n to be derived at step d of trip t when selecting a travel alternative $i \in C^T_{ntd}$:

$$U^i_{ntd} = \sum_{k=1}^{K} \beta^k \cdot \hat{x}^{ik}_{ntd} + \sum_{k=1}^{K} \theta^k \cdot \tilde{x}^{ik}_{ntd} + \alpha^i_n + \varepsilon^i_{ntd}. \tag{2}$$

This specification assumes that individuals perceive each alternative i as a bundle of K attributes: $x^{i1}_{ntd}, x^{i2}_{ntd}, \ldots$. More specifically, as each of these attributes may be uncertain, we model them by assuming a mean-variability model with means $\hat{x}^{ik}_{ntd}$, variabilities $\tilde{x}^{ik}_{ntd}$ and no covariabilities. The indexing of n, d and t represents how an individual's *perception* of the attributes of travel alternatives is conditional on the information acquired at earlier decision steps. This conditionality works as follows: the perception of an attribute k for which a message $\bar{x}^{ik}$ is received through information acquisition at an earlier step is characterized by a mean of magnitude $\bar{x}^{ik}$ and a variability of magnitude zero (an exception is the activation of the early warning function for travel times, see Section 3.4). In other words, we assume the information to be fully reliable. The mean and variability of an attribute for which no information was previously acquired equal those provided to the traveler at the outset of a trip.

Parameters β^k represent preferences with respect to the mean of attribute k, and parameters θ^k reflect the traveler's valuation of the variability associated with the same attribute. An error component α^i_n is constant across trips and decision steps for the same individual and represents the individual's intrinsic preferences for specific travel alternatives; as such, it accounts for heterogeneity in traveler response. The extreme-value variable ε^i_{ntd} is i.i.d. and varies across individuals, trips and decision steps.

In the next section we shall derive the utility functions for information acquisition options. It is important to note that our specification of the utility of information acquisition involves no additional parameters beyond those in Eq. (2), with the exception of parameters related to the costs of the information. This enables us to limit the number of parameters needed to estimate the model. It also allows us to use observed information acquisition behavior directly to estimate travelers' valuation of the mean attributes of travel alternatives (β^k) and the variability attached to them (θ^k).

3.4. Utility specification of information acquisition options

We define the utility of acquiring information piece r at step d of trip t by individual n as the utility that the individual anticipates after the information is acquired. This utility is to be derived from the choice set of travel alternatives at step d + 1 (note that when faced with the choice of *whether or not* to acquire information, it is the expected *incremental* utility from the travel choice set that matters. In our model however, we are concerned with modeling choices from a choice set that contains information acquisition options as well as travel alternatives. This leads to the specification of information utility in *absolute* terms). As a result, the utility of the information depends on the following anticipations of individual n at step d of trip t (with anticipation denoted as the symbol $\smile$):

1. The individual's anticipation of the composition of the travel choice set at step $d + 1$, which depends on the information acquired at step d: $\breve{C}^T_{ntd+1}$.
2. The individual's anticipation of the utility of travel alternatives in the anticipated choice set at step $d + 1$, which depends on the information acquired at step d: $\breve{C}^T_{ntd+1}$. This utility is itself fully specified by applying Eq. (2) based on the following two anticipations of the individual:
   a. The individual's anticipation of the attributes of travel alternatives in this choice set at step $d + 1$, which depends on the acquired information at step d.
   b. The individual's anticipation of the (in the eyes of the analyst) unobserved parts of the utility of these alternatives at step $d + 1$: $\breve{\varepsilon}^i_{ntd+1}$ and $\breve{\alpha}^i_n$ Note that as the α's are time-unspecific, $\breve{\alpha}^i_n = \alpha^i_n$. We furthermore assume $\breve{\varepsilon}^i_{ntd+1}$ to be independent from ε^i_{ntd+1} and ε^i_{ntd} for all i's.

We can now formalize the random utility of acquiring a particular piece of information r in terms of the expectation (from the analyst's point of view) of the maximum anticipated random utility of the travel choice after the information has been acquired, minus information costs.

$$U^r_{ntd} = E\left(\max_{i \in \breve{C}^T_{ntd+1}} \{\breve{U}^i_{ntd+1}\}\right) - c^r_{ntd} + \delta^r_n + \varepsilon^r_{ntd}. \tag{3}$$

The perceived cost, c^r_{ntd}, of acquiring the piece of information r may consist not only of monetary costs, but also costs in terms of time, effort, attention, etc. Variation in the unobserved utility of a piece of information across individuals, trips and decision steps is captured here by two error components. The variable δ^r_n represents an agent effect that is constant across trips and decision steps for the same individual and reflects the individual's latent preference for acquiring a particular piece of information r (and as such accounts for heterogeneity in traveler response). Variable ε^r_{ntd} is an i.i.d. error component that varies across individuals, trips and decision steps. What anticipations a traveler might have regarding the travel choice set and the attributes of alternatives therein depends on the type of information he or she acquires. These anticipations are derived below for each of the types of information considered, as is the utility of their acquisition.

3.4.1. Assessment of known alternatives (A)

Acquiring a piece of information related to the assessment of known alternatives (denoted r^A) does not add any alternative to the choice set, so the individual anticipates no changes in the composition of the choice set: $\breve{C}^T_{ntd+1} = C^T_{ntd}$. However, the individual's anticipation of the utility of travel alternatives in this choice set does depend on acquired *assessment* information. We assume that the individual does not anticipate that acquiring information about alternative j's attribute l will alter his or her perceptions of the attributes of any alternative $i \neq j$, or of attributes $k \neq l$ of alternative j. However, we do assume that the individual does anticipate his or her perception of alternative j's attribute l to be affected by acquiring *assessment* information. The individual anticipates that, conditional to receiving some estimate $\bar{x}^{jl}$ for j's attribute l, he or she will obtain the true value of attribute $\bar{x}^{jl}$ with zero variability attached. Note that, for simplicity of presentation, here we cover the case of acquiring information for only *one* of the attributes of a known option. Extending these formulas to the simultaneous acquisition of estimates for multiple attributes is straightforward.

Of course, when considering whether to assess attribute x^{jl}, the individual does not know what estimate (message) he or she will receive. Therefore, the utility of the assessment must be integrated over the probability density function representing his or her beliefs regarding what message will be received. This density function is denoted as $f_{ntd}(\bar{x}^{jl})$ and depends on the traveler's initial perceptions of the attribute as well as on the perceived reliability of the information. Together, this gives the following specification of the utility of acquiring a piece of information r of type A:

$$U^{r^A}_{ntd} = \int_{\bar{x}^{jk}} \left(E\left(\max_{i \in \breve{C}^T_{ntd+1}} \{\breve{U}^i_{ntd+1}\}\right) \cdot f_{ntd}(\bar{x}^{jl})\right) d\bar{x}^{jl} - c^{r^A}_{ntd} + \delta^{r^A}_n + \varepsilon^{r^A}_{ntd}. \tag{4}$$

As $\breve{\varepsilon}^i_{ntd+1}$ is assumed to be independent of ε^i_{ntd+1} and ε^i_{ntd} for all travel alternatives, the expected maximum of random utilities $\breve{U}^i_{ntd+1}$ can be written in terms of the logarithm of the sum, over all $i \in \breve{C}^T_{ntd+1}$, of the exponentials of $\breve{U}^i_{ntd+1} - \breve{\varepsilon}^i_{ntd+1}$. This leads to:

$$U^{r^A}_{ntd} = \int_{\bar{x}^{jk}} \left(\ln\left[\sum_{i \in \breve{C}^T_{ntd+1}} \exp(\breve{V}^i_{ntd+1} + \alpha^i_n)\right] \cdot f_{ntd}(\bar{x}^{jl})\right) d\bar{x}^{jl} - c^{r^A}_{ntd} + \delta^{r^A}_n + \varepsilon^{r^A}_{ntd}. \tag{5}$$

Here, $\breve{V}^i_{ntd+1} = \breve{U}^i_{ntd+1} - \breve{\varepsilon}^i_{ntd+1} - \alpha^i_n$.

3.4.2. Generating unknown alternatives (G)

Acquiring a type G piece of information (denoted as r^G) generates a previously unknown travel alternative such as j, and the true values of all of its attributes are provided. We thus assume that the individual anticipates his or her choice set of travel alternatives to be enriched with the acquired travel alternative $\breve{C}^T_{ntd+1} = \{C^T_{ntd}, j\}$ once the information is received.

The individual would not anticipate generating travel alternative j to alter his or her perceptions of the attributes of any alternative in this choice set that is not generated by the information service. However, the individual would anticipate his or her perceptions for all L_j attributes of the generated alternative j to be given by the received message. Because the individual knows the information is fully reliable, he or she anticipates that, conditional to receiving some bundle of estimates $\bar{x}^{j1},\ldots,\bar{x}^{jL_j}$, his or her perception of the attributes of the generated alternative will equal the received estimates with no variability attached. Of course, here again the individual does not know what estimates he or she will receive when generating alternative j. Therefore, we again need to integrate over the probability density function describing what message the individual thinks he or she might receive $f_{ntd}(\bar{x}^{jl})\cdot\ldots\cdot f_{ntd}(\bar{x}^{jL_j})$. Using the log-sum formulation, this leads to the following specification of the utility of acquiring information r^G:

$$U^{r^G}_{ntd} = \int_{\bar{x}^{j1}\ldots\bar{x}^{jL_j}} \left(\ln\left[\sum_{i\in\breve{C}^T_{ntd+1}} \exp(\breve{V}^i_{ntd+1}+\alpha^i_n) \right] \cdot f_{ntd}(\bar{x}^{j1})\cdot\ldots\cdot f_{ntd}(\bar{x}^{jL_j}) \right) \cdot d\bar{x}^{j1}\cdot\ldots\cdot d\bar{x}^{jL_j} - c^{r^G}_{ntd} + \delta^{r^G}_n + \varepsilon^{r^G}_{ntd}. \tag{6}$$

3.4.3. Activating the early warning function (W)

This type of information differs from the previous two types (A and G) in that no message is received directly after the information is acquired. Rather, information bit r^W is an insurance against strongly deviating travel times. By activating the early warning function, the individual receives a message if the travel alternative he or she is about to choose has a travel time, denoted as attribute l, that deviates strongly (for example, by more than g minutes) from the usual travel time under normal conditions, for instance due to an accident. This message does *not* contain an estimate for the travel time. Because the early warning function does not add any alternative to the choice set, the individual anticipates no changes in the choice set upon acquiring this type of information $\breve{C}^T_{ntd+1} = C^T_{ntd}$. Again, the individual's anticipation of the utility of travel alternatives in this choice set depends on his or her anticipated perception of the attributes of these alternatives. The individual does not anticipate activating the early warning function to alter his or her perceptions of the attributes of alternatives, other than travel times, in his or her choice set.

However, the individual logically anticipates type W information to alter his or her perceptions of attribute l, travel time, for all alternatives. Although he or she knows that the anticipated mean travel time does not change as a result of activating the early warning function, it is assumed that he or she will anticipate that the variability of travel time of all alternatives is reduced to some number z if the variation does not already equal zero as a result of earlier information acquisition. Directly using the log-sum formulation gives the following specification of the utility of acquiring information r^W:

$$U^{r^W}_{ntd} = \ln\left[\sum_{i\in\breve{C}^T_{ntd+1}} \exp(\breve{V}^i_{ntd+1}+\alpha^i_n) \right] - c^{r^W}_{ntd} + \delta^{r^W}_n + \varepsilon^{r^W}_{ntd}. \tag{7}$$

3.5. Choice probabilities and sample likelihood

Now that the utilities have been specified, we can formulate the probability that an individual n at decision step d of trip t will choose to acquire some form of travel information or execute one of the available travel alternatives. Deriving the choice probabilities for information acquisition options and travel alternatives involves integrating over the i.i.d. extreme-value terms as well as over the individual specific error terms. Let us briefly revisit these error components before formulating the choice probabilities and the sample likelihood.

First consider the error components of the travel alternatives. As specified in Eq. (2), these consist of i.i.d. extreme-value terms $\varepsilon^i_{ntd},\varepsilon^j_{ntd},\ldots$ and individual specific intrinsic preferences for travel alternatives $\alpha^i_n,\alpha^j_n,\ldots$. Note again that besides entering the utilities of travel alternatives, the latter individual-specific error components also codetermine the utilities of information acquisition options as is shown in Eqs. (5)–(7). For example, a traveler's dislike of public transit will be reflected in his or her disinclination to acquire public transit information. Then there are error components that relate directly to the information acquisition options, consisting of i.i.d. extreme-value components $\varepsilon^r_{ntd},\varepsilon^s_{ntd},\ldots$ and individual-specific preferences for different pieces of information $\delta^r_{ntd},\delta^s_{ntd},\ldots$ (or different types of information $\delta^{r^A}_{ntd},\delta^{r^G}_{ntd},\delta^{r^W}_{ntd}$). This leads to the following formulation of choice probabilities, unconditional to the i.i.d.-error components, but conditional on the individual-specific error components $\alpha^i_n,\alpha^j_n,\ldots$ and $\delta^r_n,\delta^s_n,\ldots$:

$$P(I_{ntd}=r|\alpha^i_n,\alpha^j_n,\ldots,\delta^r_n,\delta^s_n,\ldots) = \frac{\exp(V^r_{ntd}+\delta^r_n)}{\sum_{s\in C^I_{ntd}}[\exp(V^s_{ntd}+\delta^s_n)] + \sum_{i\in C^T_{ntd}}[\exp(V^i_{ntd}+\alpha^i_n)]}, \tag{8}$$

$$P(T_{ntd}=i|\alpha^i_n,\alpha^j_n,\ldots,\delta^r_n,\delta^s_n,\ldots) = \frac{\exp(V^i_{ntd}+\alpha^i_n)}{\sum_{r\in C^I_{ntd}}[\exp(V^r_{ntd}+\delta^r_n)] + \sum_{j\in C^T_{ntd}}[\exp(V^j_{ntd}+\alpha^j_n)]}, \tag{9}$$

where V^r_{ntd} and V^s_{ntd} represent the deterministic parts of the utility of particular information acquisition options r and s; V^i_{ntd} and V^j_{ntd} represent the deterministic parts of the utility of executing particular travel alternatives i and j. By using the above formulations and applying the notation of Eq. (1), we now have the means to calculate the unconditional sample likelihood (denoting $\alpha_n^i, \alpha_n^j, \ldots$ by α and $\delta_n^r, \delta_n^s, \ldots$ by δ):

$$L = \prod_{n=1}^{N} \int_{\alpha,\delta} \left(\prod_{t=1}^{T_n} P[(I_{ntd}, d = 1, \ldots, D_{nt}), T_{ntD_{nt}+1} | \alpha, \delta] \cdot f(\alpha, \delta) \right) d(\alpha, \delta). \quad (10)$$

4. The estimation of the model and results

Before reporting estimation results, we identify how we operationalized aspects of our model to match the data obtained (Section 4.1) and discuss which parameters were estimated (Section 4.2).

4.1. Operationalization of the model

In order to match the model to the available data, three types of additional operational assumptions need to be made: The first issue is to specify the mean-variability variables in Eq. (2). Let us first consider the starting situation, containing "best guesses" and "confidence intervals" for attributes. Best guesses are regarded as proxies for mean values, and the lengths of the confidence intervals are regarded as proxies for the variability of the attributes. As regards waiting times for trains, $0.5 * \text{headway}$ is used as a proxy for best guess-waiting time and headway is used as a proxy for waiting-time variability. After the information about an attribute is received, we assume that the mean value takes the value of the message received and variability drops to zero. Note that these distributions match those that are used to generate the actual attributes of travel alternatives. The second issue concerns the probability density functions that describe what messages the traveler believes he or she might receive when acquiring information. Regarding the assessment of known alternatives, and given fully reliable information, we assume that a traveler believes that messages are drawn from a normal distribution with his or her best guess as a mean and one quarter of the length of the associated confidence interval as a standard deviation. Regarding waiting time for trains, presented to participants through a headway ("a train departs every x minutes"), the traveler's belief of what message he or she may receive when acquiring information is assumed to consist of a uniform distribution between 0 and x. Regarding seat availability this belief is assumed to consist of a discrete distribution between "yes", coded as 1, and "no", coded as 0, each having a probability of occurrence of 50%.

We need to make additional assumptions about generating alternatives because no best guesses and confidence intervals for unknown alternatives are presented to the participant at the outset. As regards the disclosure of travel times and the costs of unknown alternatives, we need to specify both the means and the standard deviations of the normal distributions from which the traveler is assumed to believe the messages are drawn when an unknown alternative is generated. For the standard deviations, we assume that the participant knows the length of the respective confidence intervals (and therefore the standard deviations of the distributions for travel times and costs) for the unknown alternatives, just as he or she does for the known alternatives. This is a relatively safe assumption, given that these lengths are invariable over all trips in the starting situation. For the means, we assume the following: participants are aware of the fact that best guesses for an alternative's travel time and cost were drawn randomly from two values, a high and a low one. We assume that they believe that the average of these two values is the mean of the distribution from which the messages are drawn when an unknown alternative is generated. As for "seat availability" in trains, we assume that participants anticipate average availability, coded as 0.5. The third set of additional assumptions refers to travelers' beliefs with respect to how travelers believe activating the early warning function affects the length of their confidence interval for travel times. In the experiment, early warnings were set to be given as of a deviation of more than 7.5 min from the best guess travel times. Although we did not inform participants of this exact number, we assume they believed that the trigger was set at this level. As a result, we assume that the anticipated length of the confidence interval for travel times after the early warning function was activated was 15 min (0 ± 7.5 min).

4.2. Parameterization

We estimated a car constant, representing a preference for the car as a travel mode over the train, and we let the sociodemographic factor "driver's license holder" interact with this constant. Furthermore, we estimated mode-unspecific parameters for travel time and travel cost (for both the mean value and variability terms). For the train options, additional parameters were estimated concerning mean waiting time and its variability as well as seat availability. After a preliminary analysis, it was decided to dummy code the trip purpose as "business" for the important business meeting context and to have it interact with (the proxies for) mean travel and waiting time and their variability. We also estimated parameters that concerned the monetary costs of information acquisition. Furthermore, we estimated a type-unspecific information constant as well as type-specific constants representing the *additional* utility of activating the early warning function and of generating unknown alternatives. It was decided to have education level interact with the general constant of information acquisition, whereby the increasing levels in the Dutch educational system were coded from 1 to 5.[1] Finally, we estimated the

[1] Coding this intrinsically ordinal variable as an interval variable was done to keep the model parsimonious. Note that it is generally accepted throughout the social sciences to code 5-point ordinal variables as interval ones.

Table 3
Estimation results.

Variable	Parameter	*t*-Statistic
Travel-related variables		
Car constant	0.4053	0.990
Sigma (car constant)	0.6092	4.649
Driver's license holder dummy[a]	0.5690	1.374
Travel time (minutes)	−0.1552	−14.228
Travel time variability (minutes)	−0.0125	−3.216
Travel costs (Euros)	−0.5512	−13.378
Travel costs variability (Euros)	−0.0504	−3.228
Waiting time (train, minutes)	−0.1076	−4.206
Waiting time variability (train, minutes)	0.0720	4.637
Seat availability (on public transit constant)	0.7461	2.887
Travel time * business[b]	0.0180	1.193
Travel time variability * business[c]	−0.1016	−11.872
Waiting time * business[d]	−0.0246	−0.720
Waiting time variability * Business[e]	−0.0996	−4.138
Variables related to information costs		
Information acquisition constant	−4.7978	−5.804
Sigma (information acquisition constant)	1.4038	8.410
Monetary costs of information acquisition (Euros)	−1.7171	−9.219
Early warning constant[f]	0.4429	1.138
Sigma (early warning constant)	2.2681	8.670
Option-generation constant[e]	1.7543	15.779
Education level * information acquisition[e]	0.5075	2.504
Model statistics		
0-log likelihood	−4477	
Log likelihood at convergence	−3103	
Number of cases	1490	

[a] To be added to the car constant.
[b] To be added to the travel time parameter.
[c] To be added to the travel time variability parameter.
[d] To be added to the waiting time parameter.
[e] To be added to the waiting time variability parameter.
[f] To be added to information acquisition constant.

standard deviations of the individual-specific random parts of the car constant, the generic information acquisition constant and the early warning constant, in order to: represent potential heterogeneity in the population; reflect how multiple choices made by the same individual may be correlated; and account for nesting effects between different travel modes and information acquisition options.

4.3. The estimation of the model and results

The model as conceptualized in Section 3 and operationalized in Section 4.1 was coded in GAUSS 7.0. The computation of the likelihood function involved the evaluation of two sets of integrals: one three-dimensional integral captured the intrinsic individual-specific preferences for traveling by car, for acquiring information in general and for activating the early warning function (the $f(\alpha,\delta)$ in Eq. (10)). A second set of integrals reflected that travelers do not know beforehand what message they will receive when they are acquiring information. The utility of acquiring information was therefore specified by integrating the utility of receiving a particular message over the probability density function representing which message might be received. (These density functions appear as $f_{ntd}(\bar{x}^{jl})$ and $f_{ntd}(\bar{x}^{jl}) \cdot \ldots \cdot f_{ntd}(\bar{x}^{jL_j})$ in Eqs. (5) and (6).) The dimensionality of these integrals depended on the information acquired: e.g., assessing a known alternative's travel time involved the evaluation of a one-dimensional integral, and generating a new car option involved a two-dimensional integral (as messages for travel times and costs were received in the process of generating alternatives). Both sets of integrals were evaluated through simulation, using 250 Halton draws per individual per dimension for the error components and 50 Halton draws per dimension for the message probability functions. For each of the 250 multidimensional draws for the error components, 50 draws were made to simulate messages from the information service. Kenneth Train's GAUSS code was gratefully used to make the draws. Experimenting with different numbers of draws for the message integrals shows that 50 draws is a sufficient number for their evaluation.

Table 3 shows the estimation results. As our model differs from existing approaches in several nontrivial ways (the sequential nature of traveler response to information is acknowledged, multiple types of information are considered, and message-anticipations are explicitly considered), we will first evaluate the performance of the model as a whole. As can be seen in table 3, the model fit is good and it appears that the parameters are generally significant and of the expected sign. Together, this suggests the validity of the proposed model specification and of the assumptions made to operationalize the model.

A detailed look at the parameters reveals some more interesting results. There appears to have been no significant preference for the car mode over traveling by train, but substantial heterogeneity does exist with respect to mode preferences (as indicated by the sigma car constant). For most trip purposes travel time itself was more negatively valued than its variability. For nonbusiness trip purposes, waiting time variability was even found to have had a small positive valuation. For trips to important business meetings, however, travel time variability was valued in a strongly negative way. For these trips, no additional negative valuation of mean travel time was found. The implied values of mean travel time were 17 Euros per hour for all trip purposes. The implied values of travel time variability (in terms of the length of the confidence interval) were 1.3 Euros per hour for nonbusiness trips and 12.4 Euros per hour for business trips.

The information acquisition parameters display a large and negative information acquisition constant. Since a separate parameter was estimated for monetary information costs, this constant can be regarded as representative for all the generalized nonmonetary costs of information acquisition, incorporating costs of effort, attention, time, etc. These costs appear to be substantial. Note, however, the large and positive parameter for interaction between the level of education and the information constant. Individuals with a relatively high level of education on average incurred substantially less generalized nonmonetary costs when acquiring information compared to those with only primary school education (or they perceive the benefits of the information higher than others). This interaction between education level and information utility is in line with earlier findings (e.g. Petrella and Lappin, 2004) that higher education levels induce more information acquisition.

The significant and rather substantial constant for generating alternatives indicates that on average individuals derive more utility from generating unknown alternatives than they do from other types of information acquisition. Since the "economic" value of information acquisition was fully specified in terms of the utility of choosing from travel alternatives after the information was received, the fact that the additional constant for generating alternatives was significantly different from zero indicates that travelers have intrinsic preferences for some types of information over others that do not necessarily coincide with the economic value of the information.

5. Conclusions

An integrative discrete-choice model of traveler response to pre-trip information acquisition was developed. The model contributes to the literature by taking into account the sequential nature of traveler response to a variety of information types. We postulated that a traveler decides to acquire information based on the utility of the anticipated travel choice situation after the information is received, and created our model accordingly. Once information has been acquired, the received messages alter the traveler's perceptions of the number of known travel alternatives or the variability attached to their attributes. Subsequently, the traveler must again choose from a choice set containing options for additional information acquisition as well as travel alternatives. This means that each trip the traveler makes involves a potentially large sequence of decisions, consisting of a number of information acquisition steps followed by a travel choice. Due to its generic specification, our model is able to describe traveler response to a wide variety of travel information types, including – but not limited to – the ones considered in this paper, using a limited number of parameters with intuitive interpretation.

We estimated the model on data collected through a travel simulator experiment which provided participants with an abstract multimodal travel network and a personal intelligent travel assistant that was able to: provide estimates for the uncertain attributes of known alternatives; generate formerly unknown travel alternatives; and warn the traveler if the travel time of an alternative about to be undertaken greatly exceeded their expectations. Estimation results show that a substantial increase in log likelihood is achieved, although the rather limited amount of only 21 parameters was used to predict choices from sets containing up to 40 different choice options (travel alternatives and information acquisition options).

In terms of practical implications, the application of our model could increase the accuracy of microsimulation models of travel demand by putting more focus on how information provision may influence traveler behavior at the disaggregate level, and thus influence traffic flows at the aggregate level. Presumably, models that address such aspects of travel behavior with increased rigor would be able to provide increasingly reliable evaluations of the effect of a variety of demand measures based on travel information. For example, our model could facilitate the evaluation of different sequences of information provision by taking into account the order in which different pieces of information are provided to travelers. This, in turn, could facilitate the design of optimal information provision sequences in terms of expected behavioral adaptation among travelers. More generally speaking, this paper highlights the importance of acknowledging travelers' choice sets and their perceptions of the (uncertain) attributes of alternatives, when estimating travel choice models based on revealed choice-data. As is well known, particularly in the context of choice set inference, incorrect assumptions are likely to lead to biased parameter estimates. Since, in the context of a revealed choice-datacollection, travelers' choice sets and perceived attributes of travel options are very likely to have been influenced by messages from travel information services, incorporating the process of information acquisition and response to received messages in choice models is likely to increase the quality of estimation results. The model presented here provides a means to do so.

In terms of avenues for further research, we feel it is important to test our model on other datasets. Given that the model relies on (proxies for) the beliefs a traveler has concerning the availability of different travel alternatives and information sources, and concerning the uncertainty associated with attributes like travel times and costs, data-collection based on dynamic Stated Choice-experiments seems to be the most convenient way forward. This is not to say that the model does not lend itself for testing based on revealed choice data. One may for example think of a setting in which travelers are equipped with PDAs with a GPS-module that record their information acquisitions and subsequent travel choices. In combination with questionnaires that provide additional information on the traveler's beliefs and preferences, such choice-data will allow for the testing of integrated models of traveler response to information. However, the collection of rich data like these remains a challenge to be met in future research efforts.

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Appendix A. Description of an observed choice-sequence (Individual 172, trip 10)

Starting situation:

- Car 1: Best guess time: 50 min; Confidence interval: between 30 and 70 min; Best guess costs: 3.5 Euros; Confidence interval: between 0 and 7.5 Euros.
- Car 2: Best guess travel time: 50 min; Confidence interval: between 30 and 70 min; Best guess travel costs: 3.5 Euros; Confidence interval: between 0 and 7.5 Euros.
- Train 1: Frequency: once every 15 min; Best guess travel time: 55 min; Confidence interval: between 37 and 73 min; Best guess travel costs: 3.5 Euros; Confidence interval: between 0 and 7.5 Euros; Seat availability: unknown.
- Train 2: Unknown (and therefore unavailable for choice).

Starting situation:

Car 1:	Best guess time: 50 minutes; Confidence interval: between 30 and 70 minutes; Best guess costs: 3.5 Euros; Confidence interval: between 0 and 7.5 Euros.
Car 2:	Best guess travel time: 50 minutes; Confidence interval: between 30 and 70 minutes; Best guess travel costs: 3.5 Euros; Confidence interval: between 0 and 7.5 Euros
Train 1:	Frequency: once every 15 minutes; Best guess travel time: 55 minutes; Confidence interval: between 37 and 73 minutes; Best guess travel costs: 3.5 Euros; Confidence interval: between 0 and 7.5 Euros; Seat availability: unknown
Train 2:	Unknown (and therefore unavailable for choice)

Observed decision sequence:	Received information:
1. *Generate train 2:*	Waiting time: 2 minutes / travel time: 57 minutes / travel costs: 5 Euros / no seat available.
2. *Assess waiting time for train 1:*	Waiting time: 2 minutes.
3. *Assess travel time for train 1:*	Travel time: 70 minutes.
4. *Assess travel time for car 2:*	Travel time: 61 minutes.
5. *Assess travel time for car 1:*	Travel time: 54 minutes.
6. *Choose car option 1.* (Realized travel time: 54 minutes; realized travel costs: 1 Euro)	

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