USDOT Region V Regional University Transportation Center Final Report

NEXTRANS Project No. 080PY04

Integrated Deployment Architecture for Predictive Real-Time Traffic Routing Incorporating Human Factors Considerations

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TECHNICAL SUMMARY

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Title

Integrated Deployment Architecture for Predictive Real-Time Traffic Routing Incorporating Human Factors Considerations

Introduction

As Advanced Traveler Information Systems (ATIS) are being more widely accessed by drivers, understanding drivers' behavioral responses to real-time travel information through ATIS and its consequential benefits are important to the widespread deployment of ATIS technologies. Traditionally, the benefits of real-time travel information have been explored in two dimensions: (i) improving personal travel experience by reducing travel time and its uncertainty in drivers' decision-making, and (ii) enhancing the performance of the entire traffic network by motivating drivers to use less congested routes. However, despite the strengthened effectiveness of real-time travel information with the recent increased deployment of ATIS through various sources, the increasing amount of information from multiple sources may cause extra stresses in perception of the information in relation to drivers' cognitive ability and the particular travel context. In addition, the psychological benefits from the information in relation to the better knowledge or reassured feeling have not been addressed in the literature. In this context, this study proposes an analytical framework to understand the comprehensive benefits of real-time travel information with consideration of the qualitative and cognitive limitations in the processing procedure. Human factor issues play a critical role in the framework, especially when multiple and heterogeneous sources of information exist. The proposed framework from the psychological aspect allows systematic analysis of the benefits of real-time information that include conventional values such as travel time savings as well as the qualitative and psychological attributes that affect behavioral responses to the real-time information.

Findings

In this study we propose an integrated framework of psychological processes of individual users with respect to real-time travel information received. Within the sequential process, three psychological effects are defined based on the distinct characteristics associated with information-related stresses. First, cognitive burden represents human-factor-related effects that increase drivers' stress of processing an influx of real-time travel information, due to the difficulty of comprehending the information with a limited cognitive capacity of drivers and within a limited time before making decisions. Second, cognitive decisiveness is a psychological state that depends on the stress due to the gap between the level of the information that drivers desire to receive and the level of the information that the drivers have been received and comprehended. Cognitive decisiveness can be enhanced by the increased awareness of traffic situations consistent with real-time travel information; or it can be reduced if the information bears exogenous uncertainty possibly due to the inconsistency between the information from different sources. Note that cognitive decisiveness is not impacted by whether the information indicates favorable traffic situations or not. Third, emotional burden illustrates an emotional spectrum of drivers' secure feeling corresponding to the perceived favorableness of information, labeled as unfavorableness stress, in relation to the travel context of drivers. As a result of the psychological effects of real-time travel information, individual drivers experience different levels of satisfaction based on their experienced travel time. The satisfaction can be expressed as a latent variable for psychological benefits of real-time travel information in the multiple indicator multiple cause (MIMIC) modeling structure, which involves latent psychological effects as well as explanatory variables including individual attributes, travel context, and information characteristics.

Recommendations

This research suggests that the effectiveness of real-time routing information provided through Advanced Traveler Information System (ATIS) is not only related to physical benefits in terms of travel time savings for individual users, but also to psychological benefits for individual users representing improved mental states throughout the travel or qualitative evaluation of travel experience. By including such psychological aspects in investment decisions for infrastructure, this approach will help support the justification of investment from the perspective of quality of travel experience, and further improve the design of real-time travel information to be effective in terms of users' perception for public and private information providers.

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TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER 1. INTRODUCTION

1.1 Background and motivation

As en-route real-time travel information is provided to drivers through Advanced Traveler Information Systems (ATIS), the benefits of such real-time travel information need to be well-understood. The benefits of real-time travel information can be explored in two dimensions that are consistent with the objectives of the information provision: (i) to improve personal travel experience by reducing travel time and its uncertainty in drivers' decision making and, in parallel, (ii) to enhance the performance of the entire traffic network by motivating drivers to use less congested routes. In order to achieve these objectives, considerable efforts have been made to use the real-time travel information as an effective tool to affect drivers' behavioral responses. For example, recent developments in mobile communication technologies maximize the effectiveness of real-time travel information by providing drivers on-demand customized information and, in turn, potentially enhancing the benefits from the information.

Understanding drivers' behavioral responses to real-time travel information and consequent benefits is one of the critical links in the interactive relationships among multiple ATIS stakeholders. As shown in Figure 1.1, user benefits of real-time travel information for both individual drivers and system operators are assessed by policy makers as the value of the ATIS which can support further investments in the system. In this process, drivers' behavioral responses (e.g., route choice decisions) are fed back to the ATIS to generate new information associated with the evolution of traffic conditions. In addition, given the recent increased deployment of ATIS through various sources, the effectiveness of real-time travel information has been largely strengthened so that drivers can make more-informed decisions and with greater confidence. However, the increasing amount of information from multiple sources may cause extra stress in perception of the information in relation to drivers' cognitive ability and the particular travel context. An analytical model is needed to evaluate the additional benefits/burden of real-time information to drivers. Thus, understanding driver behavioral responses under real-time travel information provision is one of the most significant challenges in studies related to real-time travel information and ATIS (e.g., Peeta et al., 2000; Abdel-Aty and Abdalla, 2006; Ben-Elia and Shiftan, 2010).

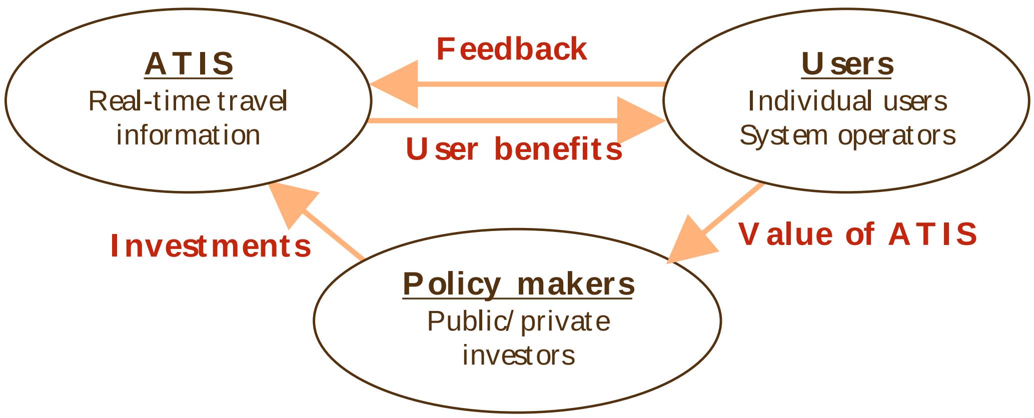

Figure 1.1 Interactions among ATIS, users and decision-makers

1.2 Study objectives

The primary objective of this study is to develop an integrated analytical architecture to understand the comprehensive benefits of real-time travel information with consideration of the qualitative and cognitive limitations in processing real-time travel information that involves human factor issues, especially when multiple and heterogeneous sources of information are used in ATIS. The proposed approach from the psychological aspect allows systematic analysis of the comprehensive benefits of real-time information that include conventional values such as travel time savings as well as the qualitative and psychological attributes that affect driver behavioral responses to the real-time information. The specific research objectives in this study include:

(i) Review the current literature related to drivers decision-making behaviors under real-time travel information provision;

(ii) Explore the psychological implications of the perception and decision-making process with information according to individual attributes, travel context, and characteristics of information;

(iii) Develop a statistical modeling structure to explore the psychological effects of real-time travel information provision during the trip;

(iv) Develop a statistical modeling structure to comprehend the after-the-trip psychological benefits (satisfaction) that are affected by: (a) travel experience, and (b) the psychological effects of information provision during the trip.

1.3 Organization of the research

The remainder of the report is organized as follows. Chapter 2 reviews existing studies, including analytical models as well as interactive driving simulator experiments, on understanding drivers' perception and responses under real-time information provision. Chapter 3 presents the essential concepts of psychological terms and overview of the psychological structure that are used in the development of the proposed analytical architecture. Chapter 4 explains in detail the multiple indicators multiple causes (MIMIC) model upon which the psychological effects and corresponding benefits are modeled. The main properties of the proposed model are also discussed. Chapter 5 summarizes this study and provides potential venues for future research.

CHAPTER 2. STUDIES ON BEHAVIOR UNDER REAL-TIME TRAVEL INFORMATION PROVISION

Understanding driver behavioral responses under real-time travel information provision is one of the most significant challenges in the studies related to the development of real-time travel information and ATIS (e.g., Peeta et al., 2000; Abdel-Aty and Abdalla, 2006; Ben-Elia and Shiftan, 2010). In this context, most of the existing studies regarding the impacts or the benefits of real-time travel information can be characterized by modeling driver behavioral responses to the real-time information.

2.1 Driver behavioral responses under real-time travel information provision

One of the noteworthy approaches to accommodate driver route choice behavior under information provision is a computer simulation-based approach, which can be further categorized by the nature of decision-making mechanisms: static or dynamic. Several early studies (e.g., Mahmassani and Jayakrishnan, 1991; Jayakrishnan et al., 1994) adopt static decision-making mechanisms to address the user behaviors identified from different groups of drivers with different thresholds of travel time for the route diversion. These studies provide intuitive insights to represent the behavioral responses under different information provision strategies including the different levels of market penetration of the information. They also analyze the benefits of real-time travel information in terms of system-wise aggregate travel time savings.

By contrast, dynamic characteristics of drivers' perception and behavioral responses over time are stressed in other studies (e.g., Jha et al., 1998; Srinivasan and Mahmassani, 2000; Nakayama and Kitamura, 2000), inspired by psychological or perceptional concepts. Drivers' intentions to accept the provided information can be described using characteristics such as inertia and compliance (Srinivasan and Mahmassani, 2000). Drivers' dynamic evaluation of the information content is explained by introducing the concepts of delusion, freezing (Nakayama and Kitamura, 2000). In spite of the capability to describe day-to-day or within-day evolutions in perception and predicting the changes in behavioral responses, the simulation-based approaches are inherently unable to accommodate human-involved factors in the context of how well the information is perceived and utilized in decision-making process by heterogeneous drivers who have different characteristics and experience.

To bridge the gap, drivers' behavioral responses to the information associated with a certain travel context have been explored within decision-making models (e.g., random utility maximization) and modified to accommodate the human factors-related features in drivers' perception. For instance, rule-based fuzzy logic has been employed as a tool to demonstrate the subjective impacts of qualitatively expressed travel information on a driver perception and decision-making (e.g., Lotan and Koutsopoulos, 1993; Lotan, 1997; Peeta and Yu, 2004). Some prominent theories addressing distortions or limitations in drivers' cognition and the consequent behaviors, such as bounded rationality (Simon, 1982), prospect theory (Kahneman and Tversky, 1979), or regret theory (Quiggin, 1994), have been adopted to establish realistic modeling structures for the mechanisms of drivers' behavioral responses to real-time travel information (e.g., Chorus et al., 2006a; Chorus et al., 2008; Gao et al., 2010; Gao et al., 2011).

In contrast to such attempts to accommodate the human factors-related issues within the theoretical modeling structures, other studies (e.g., Rossetti, 2000; Dia, 2002) suggest agent-based approaches where reasoning structures are constructed to comprehend drivers' behavior in relation to real-time travel information. According to the suggested approaches, the drivers as autonomous agents in a multi-agent system with ATIS (compatible with Figure 1.1) are modeled with their qualitative attributes (e.g., beliefs, motives, impulsive actions, willingness to alter the behavior), which represent drivers' non-logical part in decision making process. In the agent-based models, therefore, the route choice decision-making can be analyzed by examining the aforementioned human factor-involved issues such as bounded rationality, limited or distorted cognition of information, and incomplete knowledge about traffic situations.

The aforementioned studies on driver behavioral responses under real-time travel information provision have been developed to explicitly emphasize the roles of drivers' qualitative characteristics including perception and psychological implications. They focus on better comprehending drivers' behavior and decision-making process, which becomes the basis for the benefits of the information for the users. In this context, the existing approaches are still unable to systematically demonstrate the processes related to drivers' perception of the information and the consequent psychological effects in parallel with the decision-making process based on the information.

This study proposes a framework for drivers' "psychological process" under the provision of real-time travel information to address psychological effects of information such as cognitive decisiveness or reassurance, and human factor issues in the perception of the information and its consequent psychological effects which have not been explored in driver behavioral research. The proposed framework consists of three parts: (i) Drivers' perception of information, (ii) psychological effects based on the perception as well as individual characteristics and travel context, and (iii) psychological benefits in terms of satisfaction. Note that the first two parts occur during the trip, and the last one occurs after the trip.

The proposed framework enables eliciting the overall trip satisfaction to reflect not only the psychological effects but also the travel time experienced from the trip. In this context, both psychological effects of the information and experienced travel time (that is the conventional benefits of information) can be addressed simultaneously and explicitly within the integrated framework. Since the psychological process considered in the proposed framework includes analyses of drivers' mental states, the corresponding data, in turn, should represent drivers' perceptional or psychological states which can be collected from human-involved experiments.

2.2 *Interactive driving simulator experiments*

Along with analytical models to understand drivers' perception and responses to real-time travel information, another significant approach to comprehend drivers' perception is interactive driving simulator experiments. Driving simulator experiments have been widely adopted in transportation research especially in areas such as road safety and infrastructure design that involve human factor issues, as controlled driving situations can be replicated with minimum risk to drivers (Matthews et al., 1998; Godley et al., 2002). Driving simulators are also highlighted as an attractive alternative to collect pseudo-realistic behavioral data to overcome some of inherent limitations of the computer simulation-based data by allowing drivers' subjective or imperfect perception of information in the course of human-involved experiments (Koutsopoulos et al., 1994; Koutsopoulos et al., 1995; Lotan, 1997; Hato et al., 1999; Mahmassani and Liu, 1999; Adler, 2001; Lu et al., 2011). Under a controlled environment, participants are invited to drive a simulator with real-time information provision in realistic traveling situations, so that the behavioral responses (including route choice decisions) observed in the experiments could be claimed to better reflect drivers' behaviors in reality.

Nevertheless, given the driver perception of the information and decision-making can be involved processes that examine not only the received real-time travel information but also other individual and situational factors (Aarts et al., 1997; Zhu and Timmermans, 2010), the current driving simulator experiments entail several limitations: (i) impaired perception of routes in tailored networks, (ii) negligence of other factors in the information that influence decision-making, (iii) pre-defined static traffic conditions, and (iv) human factor issues in the process of perceiving the information in a limited time. Among them, the first two, i.e., impaired perception of routes and negligence of other factors, are the limitations due to simplified network structure and the simulation environment, since the participants may not be able to appreciate the difference between the routes that are defined and presented in a simplified way to perceive the difference in route complexity. That is, in addition to the received information, other factors in route characteristics (e.g., presence of freeway options, toll road, different ambient traffic conditions, perceived difficulty in safe driving, etc.) contribute to the route choice decisions as well.

The third limitation is related to the inability to enable dynamic changes in traffic conditions with respect to the road hierarchy in most of the previous driving simulator experiments. While the levels of traffic congestion are not supposed to be the same on a major freeway and a minor local road, current driving simulator software cannot effectively address this problem. This issue can be addressed by an integrated module of a microscopic traffic simulation and driving simulator, so that traffic demands faced by the participants in the experiments are associated with the online output of the microscopic traffic simulation (That and Casas, 2011; Punzo and Ciuffo, 2011).

The last limitation is related to participants' perception of how the information can be easily comprehended quantitatively as well as in terms of the content of the information. As it involves the participants' cognitive ability to process such the information within a short period of time before making decisions, the perception of the information may not be perfect because of the issue of cognitive load (Katsikopoulos et al., 2000; Katsikopoulos et al., 2002).

In this study, we adopt an interactive driving simulator experiment to acquire behavioral data as well as the data of drivers' perceptional and psychological states. In order to overcome the common limitations of driving simulator experiments, the proposed interactive driving simulator experiment: (1) uses a realistic network of Indianapolis, Indiana, so that the participants configure the attraction of the routes based on not only the information but also the route attributes (e.g., freeway, toll, or safety); (2) uses varying background traffic demands which are enabled by the integration of driving simulator software and online dynamic traffic assignment in a microscopic traffic simulation package; (3) implements diverse information scenarios with multiple sources to understand participants' perceptional and psychological states depending on different information characteristics (e.g., amount, source, or content), and (4) conducts intermediate surveys to capture during-the-trip perceptional and psychological data which are not biased or distorted because of travel experience (e.g., travel time experienced), in addition to the after-trip satisfaction survey.

CHAPTER 3. PSYCHOLOGY OF REAL-TIME TRAVEL INFORMATION

Recently, interdisciplinary approaches involving psychology provide a strong synergy in transportation research related to driver behavior and decision-making under information provision, since drivers' psychological implications underneath the revealed behavioral responses (choices) can be effectively interpreted in the realm of psychology. In this context, applications of the technology acceptance models (TAM) provide an insightful framework where drivers' attitudes toward technology (here, real-time travel information) are captured using two technology acceptance measures: (i) perceived usefulness, and (ii) perceived ease of use (e.g., Xu et al., 2010; Ghazizadeh et al., 2012; Lin et al., 2013). Although these studies explore the factors that contribute to drivers' attitudes toward information use and statistical relationships among the relevant latent factors such as information quality, response time, and system accessibility (Lin et al., 2013) to demonstrate the intention to use such information, no decision-making process is involved. Therefore, the latent procedure from drivers' perception of the information and the consequential effects to the potential benefits from using the real-time travel information in terms of satisfaction or emotional relief cannot be explored within the structure of TAM.

To address these limitations, we propose a modeling structure for drivers' psychological process with real-time travel information in relation to the characteristics of the information perceived by drivers under a certain travel context. Drivers' behavioral responses under the provision of real-time travel information have been implicitly assumed seamless perception of the information within decision-making process in the previous studies (Srinivasan and Mahmassani, 1999; Mahmassani and Liu, 1999; Chorus et al., 2006a; Chorus et al., 2006b). Namely, from the modeling perspective, such decision-making models rely on certain behavioral predictions subject to randomness from several qualitative factors including driver perception which is implied in the error terms of the models. Thus, none of the perception-based psychological factors, for example, the stress from processing excessive information, reassured feelings or reduced uncertainty with real-time travel information, can be included in the structure of behavioral modeling analysis. The lack of consideration of such psychological factors in the conventional models may, in turn, result in underestimating the benefits of real-time travel information. In spite of recent attempts to address drivers' psychological phenomena related to information perception in the process of decision-making (e.g., delusion and freezing in perception; inertia and compliance in behavioral response) (Jha et al., 1998; Srinivasan and Mahmassani, 2000; Nakayama and Kitamura, 2000), it is still limited to illustrate psychological implications underneath the information perception, decision makings, and its benefits without proposing explicit mechanisms where drivers' perception and its psychological effects are systematically accommodated.

The proposed structure of psychological process is organized with separate factors influencing drivers' perception of the information and its psychological effects replaces what have been assumed and captured by the error terms in conventional behavioral models. Accordingly, the benefits of the information incorporate not only travel time savings but also the psychological benefits from the travel experience. For clarity, the terms in use and the relevant concepts are described below in the order of happening in the psychological process.

3.1 Information characteristics

Depending on the characteristics of the travel and drivers' behavior in information seeking, real-time travel information can be supplied to drivers in many different levels both quantitatively and qualitatively. To avoid possible confusion from multiple information sources and to ensure the explanatory ability of the information characteristics as factors, hereafter, real-time travel information refers to all messages that a driver receives in real time, no matter if it comes from multiple sources or how much amount it contains, in association with a single information-assisted route choice decision-making during the trip. In this sense, real-time travel information can be characterized by three inherent attributes – amount, source, and content of information – as each of them contributes to the drivers' perception of the information in different manners.

First, amount of information represents: (i) the total number of information units, each of which indicates a distinct knowledge about traffic conditions, and (ii) the length of the entire messages (e.g., number of words or characters) that the information units are expressed in. Amount of information plays an important role in the perception of the information in that the excessive amount may hinder the drivers from processing and comprehending the information.

Second, source of information represents the channel through which the information is delivered. For instance, Variable Message Sign (VMS) is a representative source for text- or graphic-based generic information to anonymous drivers at a certain location on the road, whereas personal devices with traffic information applications are the sources for generic and personalized information which is tailored to a particular driver's information needs in various possible formats – text, graphic, or voice. Note that the information from different sources are supposed to keep source-specific attributes (e.g., level of attention required, duration of possible exposure) which potentially affect drivers' perception of the information.

Third, whereas the amount and source depict the appearance of the presented information, content of information, on the other hand, refers to what the information contains. Thus, the content entails knowledge about the traffic conditions, as well as the other attributes including composition or design of information. For example, the personalized information that is tailored for a particular driver's information need is supposed to be more convincing because of the fitness of the content to the need than the generic information distributed to anonymous drivers (personalized information). In a similar manner, prescriptive information that explicitly indicates the required or recommended actions according to the traffic situations is more likely to evoke drivers' behavioral changes than the information that includes only descriptive knowledge about the traffic situations.

3.2 Drivers' psychological process with real-time travel information

Drivers' cognitive and emotional states are outcomes of the received information under the given travel context, in parallel with the decision-making process under the information provision. In order to address the qualitative process systematically, we propose a concept of psychological process with the real-time travel information. Specifically, the psychological process involves: (i) drivers' perception of the provided information according to the information characteristics, (ii) psychological effects derived from the perception, and (iii) psychological benefits in terms of satisfaction with the psychological effects as well as from travel experience including experienced travel time. As they are based on individual driver's cognition and emotion, all the steps in the psychological process should be affected by individual driver's attributes in addition to the travel context. In contrast to the perception and psychological effects happening during the trip, psychological benefits (i.e., satisfaction) are available after the end of the trip when the drivers become aware of the travel time experienced from the current trip.

3.2.1 Driver perception of real-time travel information

When real-time travel information is provided to drivers, it is first perceived by the drivers in relation to their individual attributes and travel context, followed by using it in decision-making process of route choice. In this process of route choice behavior under real-time travel information provision, only the content of the information, among the aforementioned information characteristics, is perceived to make route choice decisions. In the other words, except for individual characteristics and travel context, drivers' decision-making processes are solely influenced by the knowledge about the traffic conditions included in the information, ignoring other possible contributions of the amount or source of the information to the driver perception in relation to human factor issues.

In the proposed structure, instead, it is assumed that all of the three characteristics of information – amount, source, and content – are partly or fully responsible for drivers' perception of real-time travel information in distinguishable contexts as shown in Figure 3.1. The perception can be scrutinized by four unique criteria based on its properties: Ease of comprehension of information, consistency of information, sufficiency of information, and favorableness of information.

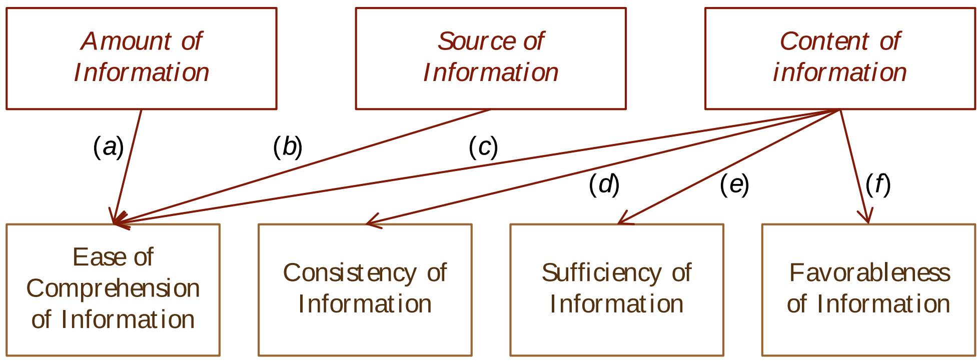

Figure 3.1 Links between information characteristics and driver perception of information

Ease of comprehension of information is a dimension that represents drivers' perception of information in terms of the effort needed to comprehend the given information reflecting heterogeneous cognitive capacity of drivers and information characteristics. Comprehending the information means, in this context, the driver understands what the real-time travel information reveals, and doesn't include its evaluation in terms of consistency or trustworthy about the knowledge that the information conveys. Thus, this dimension of perception has a linkage from the amount of information shown as link (a) in Figure 3.1, since the increased amount of information requires more efforts to process the received information in general considering drivers' limited cognitive capacity regardless the number of sources. On the other hand, the source of information also affects this dimension of perception in that the source-specific attributes (e.g., level of attention required, duration of possible exposure) and the format (e.g., text, graphic, voice) associated with the information source are relevant factors in comprehending the information by drivers (shown as link (b) in Figure 3.1). Similarly, different designs and compositions of the information are factors in comprehending the given information (shown as link (c) in Figure 3.1). For example, a direct message about route guidance is easier to understand the given information per se than the messages describing expected travel times of multiple alternative routes.

Consistency of information depicts drivers' perception of information with respect to the fact whether the content of the information is perceived to be consistent with: (i) drivers' expectations of travel experience (e.g., travel time) at the moment of information reception for the rest of the trip, and (ii) other content of the information from multiple sources if available. Although the potential value of the information might be high due to an unusual traffic situation, when the content of information is apart from one's expectation based on the prior experience and ambient traffic conditions that are being observed, the inconsistency issue is triggered so that the driver is not sure about the content of the information, especially if the driver has lower trust in real-time travel information. The consistency issue is not necessarily related to the amount of the information or the number of sources that the information is provided through, since judging consistency depends solely on its conflicting or unmatched ideas in the content of information that may or may not be from multiple sources (shown as link (d) in Figure 3.1).

Sufficiency of information explains drivers' perception of information regarding to enough, relevant content in the information to become aware of traffic situations. Sufficient information helps drivers make decisions with less uncertainty regardless their different levels of familiarities with the network and traffic conditions (i.e., link (e) in Figure 3.1). Since the discussion over sufficiency is based on the content of information that has been already comprehended, the amount of information incorporating with comprehension of information per se is not linked to the perception of information from the perspective of sufficiency. Similarly, the information source is not relevant because as long as the content of the information is sufficient enough, where the information is from or how the information is distributed to the drivers does not matter in the discussion regarding the sufficiency of information. For example, information from multiple sources could be insufficient for a driver to make a decision, whereas information from a single source could be sufficient for a driver as long as the content is relevant and enough.

Last, favorableness of information stands for drivers' perception of the information content in terms of how favorably (or unfavorably) the traffic situations are projected in the information with respect to drivers' travel context such as trip purpose or sensitivity to delay (link (f) in Figure 3.1). For instance, if real-time travel information indicates an accident ahead and a driver is in a critical situation to meet a flight departure time, the information would be perceived much more unfavorably by the driver, compared to another driver who is driving home after work.

3.2.2 Psychological effects of real-time travel information on drivers

In parallel with the typical decision-making process under real-time travel information provision, drivers go through certain changes in mental or emotional states as the result of the perception of the information in accordance with the aforementioned criteria, incorporated with travel context, situational factors and drivers' individual attributes. Here, we propose a concept of psychological effects to intuitively illustrate the explicit changes in the framework of psychological process with real-time travel information. The psychological effects entail: (i) the changes in cognitive stress associated with human factor-related issues (cognitive burden), (ii) the changes in the level of certainty with decisions (cognitive decisiveness), and (iii) the changes in the emotional feelings with the travel expectancy based on the perceived information (emotional burden).

Cognitive burden represents human factor-related effects that increase drivers' stress of processing an influx of real-time travel information, as comprehending the information with a limited cognitive capacity of drivers, within a limited time before decision-making. The presence and intensity of cognitive burden, therefore, are inferred on drivers' perception of the information in terms of the ease of comprehension of information in the given travel context. Instead of the assumption of driver's seamless perception of information in conventional decision-making models, drivers' distorted or imperfect perception of the provided information and its preceding factors can be explored in the analysis of decision-making and the benefits of real-time travel information.

Cognitive decisiveness is a psychological state enhanced by the increased awareness of traffic situations with real-time travel information, which reduces the uncertainty in route decision-making. That is, no matter whether the information indicates favorable traffic situations or not, as long as the gap is reduced between the level of the information that drivers desire to receive and the level of the information that the drivers have been received and comprehended, then the drivers will have higher cognitive decisiveness to make decisions and, further, enhance the benefits of the information provision. Among the two levels of information forming information gap, the first level desired by drivers to receive is associated with heterogeneous attributes of drivers such as trust in real-time information or network familiarity. On the other hand, the second level of information is related to drivers' perception of information in terms of consistency and sufficiency to ensure that the consistent – therefore, more trustful – information is enough to make an informed decision. Accordingly, the higher cognitive decisiveness with enough relevant real-time travel information reduces the uncertainty in route choice decisions, especially for the drivers who are traveling in an unfamiliar area and believe in the real-time information.

Emotional burden, on the other hand, represents an emotional spectrum of drivers' secured feeling corresponding to the perceived favorableness of information in relation to travel context. In contrast to cognitive decisiveness which is dependent on the sufficiency and consistency of information, this emotional status involves drivers' anticipation of travel experience based on the content of the given information in terms of favorableness to drivers' travel situations. As favorable information implies an optimistic expectation in the results of the trip, the driver will be reassured in the route choice decision process as well as throughout the rest of the trip. Consequently, the favorable information diminishes driver's stress of being worried about the results of the trip. In contrast, if the information is perceived unfavorably (e.g., congestion or delay), a negative emotional state will occur – close to anxiety, opposite to reassurance – and may incur more stress relevant to the results of the trip, although the information gap stress, at the same time, decreases because of the enhanced cognitive decisiveness with the information.

Note that the aforementioned psychological process, i.e., drivers' perception of information followed by psychological effects, occurs during the trip when real-time travel information is provided. Hence, the experienced travel time is unknown yet. Instead, the experienced travel time will be included in satisfaction after the trip where it plays a critical role to determine the level of satisfaction of travel experience and, further, the benefits of real-time travel information. Figure 3.2 illustrates the conceptual structure of the proposed model for the benefits of real-time travel information that is consistent with a conventional modeling structure (a structure containing the left two columns).

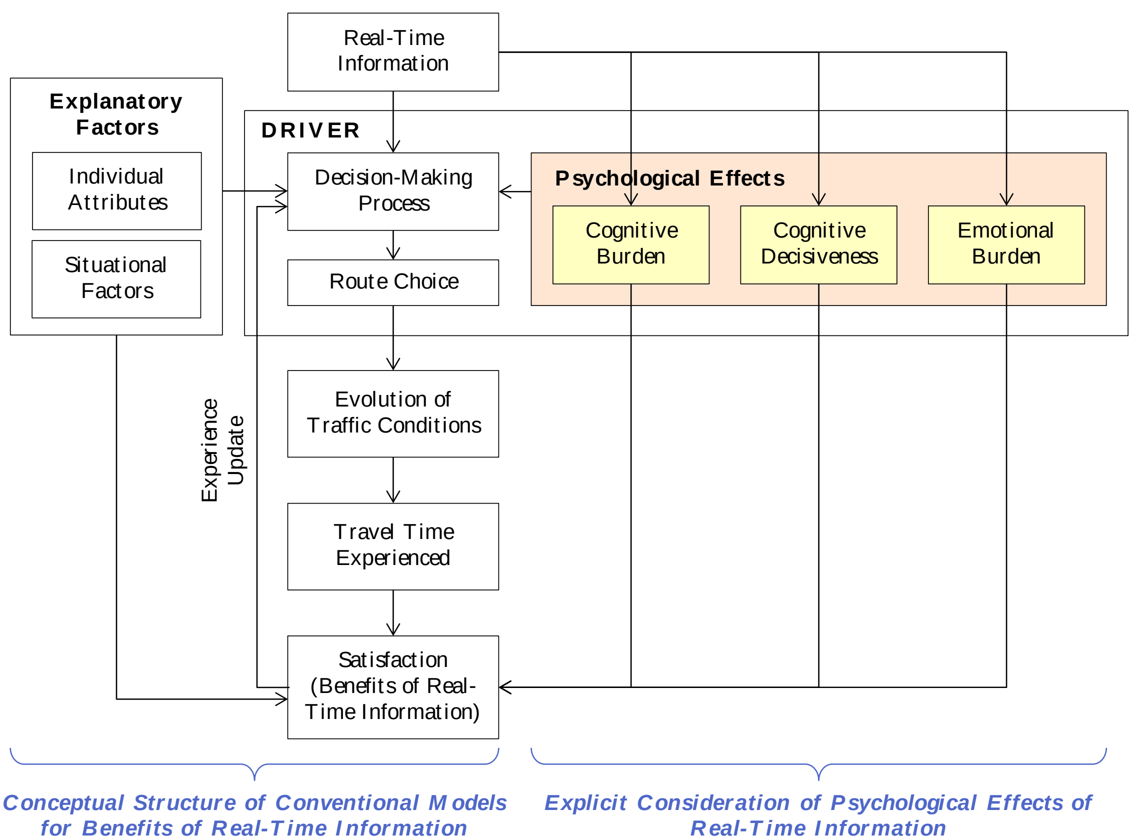

Figure 3.2 Conceptual modeling structure for benefits of real-time travel information

3.2.3 Psychological benefits of real-time travel information

The overall benefits of real-time travel information consist of: (i) physical value of travel time experienced by drivers, and (ii) drivers' evaluations of psychological state affected by travel experience with the information represented by satisfaction. The two components are correlated at a certain level but not necessarily moving proportionally or even in the same direction depending on driver characteristics and the aforesaid psychological effects incurred by the information provision. For instance, a decent travel time experienced can come up with higher satisfaction with travel time if the driver is unfamiliar with the area of traveling that he/she has no references of travel time. In this study, among the two components of benefits, the psychological evaluations of travel experience are captured in the modeling structure, so that it is able to analyze the psychological benefits explicitly and simultaneously with the numeric value of travel time experienced.

Satisfaction with travel experience

In conventional studies, travel time savings have been used to represent the benefits or satisfaction with the trip. Since identifying actual travel time savings from the current trip is not feasible for individual drivers, they instead compare the travel time experienced in the current trip with the travel time expectations based on their prior experience. In this context, satisfaction with travel experience means the satisfaction with travel time experienced. As the travel time is such a dominant factor in satisfaction with any kinds of travel outcomes, most of other satisfaction indicators should be highly correlated with the travel time experienced. However, the route choice decisions being consistent with one's preferred route are able to address another dimension of satisfaction in relation to drivers' preferences. Therefore, satisfaction with travel experience is the evaluation of various factors of travel experience including travel time experienced and route choice decisions representing travel outcomes and drivers' preferences, respectively.

Satisfaction with psychological effects

In addition to the conventional satisfaction with the travel experience, satisfaction with the psychological effects is also considered in this study to represent the improvement of travel quality with real-time travel information from the psychological point of view. It is different from the satisfaction with travel experience in that the satisfaction with the psychological effects may exist only for the drivers who received real-time travel information in the trip. This satisfaction will be evaluated as an integrated value of psychological effects throughout the trip. In this context, satisfaction with psychological effects is not necessarily to be proportional to the satisfaction with travel experience because of the dynamic traffic conditions that possibly alter the actual travel time after making decisions with the information. Figure 3.3 summarizes the process in steps from the reception of information to the psychological benefits for individual drivers. The directional links represent the specific contributions of one psychological concept to another, all of which are illustrated in this section. Note that the shaded area in the figure indicates the realm of drivers' psychological process in relation to individual attributes and travel context.

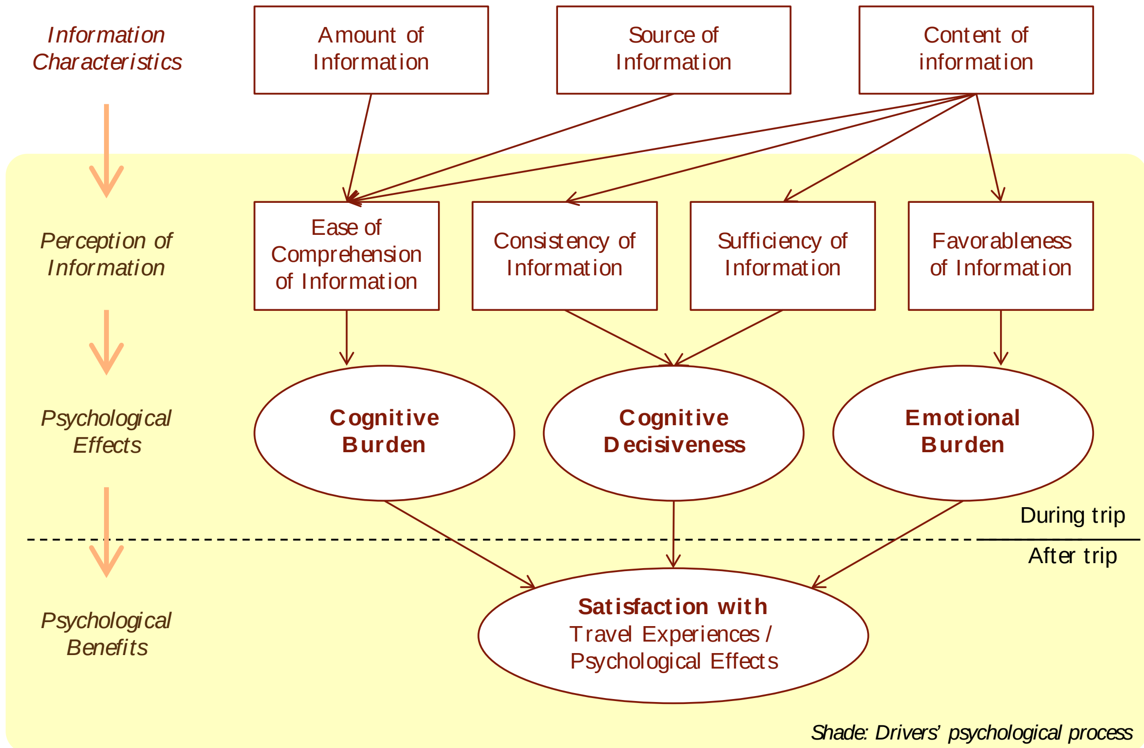

Figure 3.3 Conceptual flow of information reception and psychological process

CHAPTER 4. MODELING STRUCTURE OF PSYCHOLOGICAL PROCESS

Considering the qualitative characteristics of the problem discussed in Section 2, the selection of methodology should be based on its ability to accommodate the following concerns: (i) the presence of latent variables representing drivers' psychological states as result of perceived real-time travel information under the given situation, (ii) the presence of observed factors of drivers' individual characteristics and travel context including travel time experienced to affect such latent psychological states, and (iii) the presence of interactive and simultaneous relationships among the latent variables and observed factors in a course of psychological process of real-time travel information. In this context, structural equation modeling (SEM) is one of the most flexible approaches to statistically analyze the relationships among the latent variables and its associated indicators within the linear-in-parameters multivariate structure (Golob, 2003).

Although the general SEM is an effective modeling approach to understand latent aspects of travel behavior and values, it does not have capability of including observed factors (explanatory variables) to directly influence on the latent variables. Indeed, in many research problems, employing appropriate observed explanatory variables as cause-indicators enhances the descriptive strength of the model, especially in the case where it is highly expected that the latent variables may be affected by the variables such as demographic and/or socio-economic characteristics (Bollen, 1984; Johansson et al., 2006). Hence, in this study, we propose a modeling structure based on multiple indicators multiple causes (MIMIC) model (Bollen, 1989) which shares a SEM platform but with additional ability to handle observed variables as separate explanatory exogenous variables causing the latent variables.

As shown in Figure 4.1, there are two accompanied components in MIMIC model: (1) the latent variable measurement model, and (2) the latent variable structural model. Each latent variable is inferred by its indicators within the latent variable measurement model, while the latent variable structural model explores causal relationships among latent variables and explanatory exogenous variables.

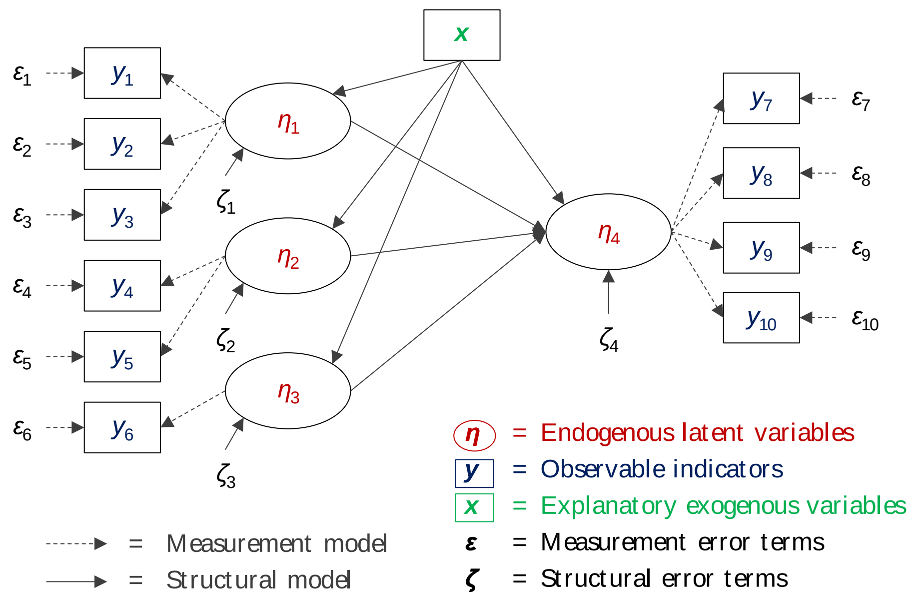

Figure 4.1 Structure of MIMIC model

4.1 Modeling of psychological effects

As illustrated above, the latent variables of the model are the psychological or emotional states affected by the perceived information under the given travel context, and its indicators are the individual drivers' answers (rates or evaluations) to the questions that are stated in the associated surveys regarding to the perceived information and satisfaction with the trip. According to the attributes of psychological effects of real-time travel information, psychological effects – cognitive burden (denoted as η^B), cognitive decisiveness (denoted as η^D), and emotional burden (denoted as η^E) – can exist for the drivers d (d = 1, …, D) who are informed en-route as many times as they receive the information. Therefore, the psychological effects should be subject to provision of each information i (i = 1, …, I) in a trip t (t = 1, …, T). Therefore, psychological effects of information provision (denoted as η_{dti}^{PE}) can be written as

$$\eta_{dti}^{PE} = \left[\eta_{dti}^{B} \; \eta_{dti}^{D} \; \eta_{dti}^{E} \right]. \quad (4.1)$$

Then, a set of indicators for the latent variables representing information perception by driver (denoted as I_{dti}^{IP}) which are collected through the surveys incorporated with the given information can be expressed as a combined set of components indicating four criteria of perception as follows:

$$I_{dti}^{IP} = \left[I_{dti}^{E} \; I_{dti}^{C} \; I_{dti}^{S} \; I_{dti}^{F} \right], \quad (4.2)$$

where, I_{dti}^{E} is a set of indicators for ease of comprehension of information, I_{dti}^{C} is a set of indicators for consistency of information, I_{dti}^{S} is a set of indicators for sufficiency of information, and I_{dti}^{F} is a set of indicators for favorableness of information for driver d, with information i, in trip t, representing the perception should be identical across drivers, trip, and information itself. On the other hand, explanatory exogenous variables that directly affect psychological effects can be defined as follows:

$$x^{d} = \left[x_{1}^{d} \; \dots \; x_{l}^{d} \; \dots \; x_{L}^{d} \right]', \quad (4.3)$$

$$x^{t} = \left[x_{1}^{t} \; \dots \; x_{m}^{t} \; \dots \; x_{M}^{t} \right]', \quad (4.4)$$

$$x^{i} = \left[x_{1}^{i} \; \dots \; x_{n}^{i} \; \dots \; x_{N}^{i} \right]', \quad (4.5)$$

where, x^{d} is the explanatory variables for individual characteristics such as demographic or socio-economic attributes of the driver, x^{t} is the explanatory variables for travel context including trip purpose, ambient traffic situations (travel demand), remaining distance of the trip, etc., and x^{i} is the explanatory variables for information characteristics comprised of amount, sources, and content of information. Subscriptions l, m, n are the indexes of the variables in each category. Time values are used as proxy to address the amount of information in two perspectives: (1) time required for recognition of text messages through a variable message sign (VMS), and (2) actual playing time (length) of voice messages through a personal device, if it is provided. The message length-based exposure time for VMS messages recommended by FHWA (Dudek, 2002) will be used to calculate the amount of information for text messages through VMS. Sources of information that are actually used to receive the information are defined as dummy variables to represent the source-specific attributes – VMS and personal device. Content of information, on the other hand, is not straightforward to quantify because of its qualitative and linguistic characteristics. Hence, in this study, the information content is characterized as a dummy variable based on its favorableness in terms of travel context, which can be represented in terms of whether it contains any accident or extra congestion implications.

As discussed in Section 2, the concept of cognitive burden can be explained by the perception indicators for the ease of comprehension of information which are obtained from the surveys through a measurement equation (4.6). At the same time, cognitive burden is also affected by characteristic variables reflecting drivers' cognitive capacities, urgency of trip, and complexity in information itself, which are described in a structural equation (4.7).

$$Y_{dti}^{B} = \Lambda_{Y}^{B}\eta_{dti}^{B} + \varepsilon_{dti}^{B} \tag{4.6}$$

$$\eta_{dti}^{B} = \sum_{l}\gamma_{l}^{B}x_{l}^{d} + \sum_{m}\gamma_{m}^{B}x_{m}^{t} + \sum_{n}\gamma_{n}^{B}x_{n}^{i} + \varsigma_{dti}^{B} \tag{4.7}$$

where the indicators for perception of ease of comprehension of information are employed to identify cognitive burden ($Y_{dti}^{B} = \left[I_{dti}^{E} \right]'$), Λ_{Y}^{B} is a matrix of factor loadings of cognitive burden η_{dti}^{B} on the corresponding indicators Y_{dti}^{B}, and γ_{l}^{B}, γ_{m}^{B}, γ_{n}^{B} are coefficients relating explanatory variables x^{d}, x^{t}, and x^{i}, respectively, to cognitive burden

η^B_{dti} for driver *d*, trip *t*, and information *i*. Also, ε^B_{dti} and ς^B_{dti} are vectors of measurement error for Y^B_{dti} and structural error for η^B_{dti}, respectively, all of which are independent to each other.

Cognitive decisiveness, on the other hand, is assumed to be associated with two distinct aspects of information perception according to its attributes: consistency and sufficiency of information. Additionally, explanatory variables such as drivers' different personalities, levels of familiarity with network, presence of accidents, and so on, can cause the variation in cognitive decisiveness. Therefore, the model for cognitive decisiveness η^D_{dti} can be written as follows:

$$Y^D_{dti} = \Lambda^D_Y \eta^D_{dti} + \varepsilon^D_{dti}, \tag{4.8}$$

$$\eta^D_{dti} = \sum_l \gamma^D_l x^d_l + \sum_m \gamma^D_m x^t_m + \sum_n \gamma^D_n x^i_n + \varsigma^D_{dti}, \tag{4.9}$$

where, the perception of consistency and sufficiency of information are used as the indicators for cognitive decisiveness ($Y^D_{dti} = \left[I^C_{dti} \;\; I^S_{dti} \right]'$), Λ^D_Y is a matrix of factor loadings of cognitive decisiveness η^D_{dti} on the corresponding indicators Y^D_{dti}, and γ^D_l, γ^D_m, γ^D_n are coefficients relating explanatory variables x^d, x^t, and x^i, respectively, to cognitive decisiveness η^D_{dti} for driver *r*, trip *t*, and information *i*. Also, ε^D_{dti} and ς^D_{dti} are vectors of measurement error for Y^D_{dti} and structural error for η^D_{dti}, respectively, all of which are independent to each other .

Similarly, the indicators for perceived favorableness of information are used to infer latent emotional burden in terms of how much reassured or nervous the driver is based on what the information implies. As emotional burden involves certain anticipation about the travel experience (e.g., travel time), drivers' individual characteristics such as attitudes toward information or sensitivity to delay related to trip purpose are expected to play significantly roles in the model as explanatory variables. The corresponding measurement and structural model for emotional burden η_{dti}^{E} is as follows.

$$Y_{dti}^{E} = \Lambda_{Y}^{E}\eta_{dti}^{E} + \varepsilon_{dti}^{E}, \tag{4.10}$$

$$\eta_{dti}^{E} = \sum_{l}\gamma_{l}^{E}x_{l}^{d} + \sum_{m}\gamma_{m}^{E}x_{m}^{t} + \sum_{n}\gamma_{n}^{E}x_{n}^{i} + \varsigma_{dti}^{E}. \tag{4.11}$$

The indicators for emotional burden are defined as $Y_{dti}^{E} = \left[I_{dti}^{F}\right]'$, Λ_{Y}^{E} is a matrix of factor loadings of cognitive decisiveness η_{dti}^{E} on the corresponding indicators Y_{dti}^{E}, and γ_{l}^{E}, γ_{m}^{E}, γ_{n}^{E} are coefficients relating explanatory variables x^{d}, x^{t}, and x^{i}, respectively, to cognitive decisiveness η_{dti}^{E} for driver *r*, trip *t*, and information i. Also, ε_{dti}^{E} and ς_{dti}^{E} are vectors of measurement error for Y_{dti}^{E} and structural error for η_{dti}^{E}, respectively, all of which are independent to each other.

Figure 4.2 illustrates the modeling structure for psychological effects associated with a specific information provision in a specific trip for a specific driver. Latent variables are indicated as ellipses, all the observed variables including perception indicators from surveys and explanatory variables are displayed as rectangles, and the relationships among the variables are represented with arrows. In the model, no causal relationship among the latent psychological effects is presented since each of them is dependent on the variations in a distinct information-related stress. Specifically, cognitive burden is based on the stress from processing the given information (information-processing stress), cognitive decisiveness depends on the stress from the modified (either reduced or enlarged) gap in knowledge about traffic situations (information gap stress), and emotional burden is based on the projected results of the trip according to the information provided (unfavorableness stress).

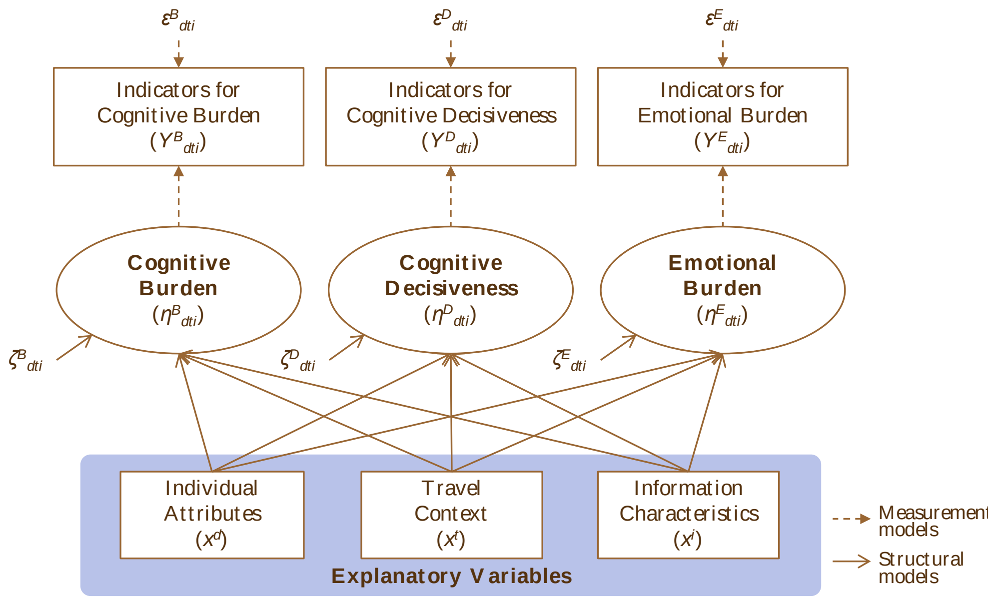

Figure 4.2 MIMIC model for the psychological effects

4.2 *Modeling of psychological benefits*

According to the previous discussion, satisfaction as psychological benefits is based on the integration of the cumulative psychological effects of the information throughout the trip and the evaluation of the experience of the entire trip. As satisfaction is generated after the trip is over when drivers become aware of travel time experienced, the modeling structure for psychological benefits should be able to include the effects of travel time experienced as one of the factors to affect the level of satisfaction. Also, to reflect the possibility of multiple information provided during a single trip, multiple sets of psychological effects according to the information provision should be addressed in the after-trip satisfaction level. In this context, satisfaction as a latent variable is defined in relation to the incorporated indicators (Y_{dt}^{S}): (i) for satisfaction with travel experience (I_{dt}^{TE}) and (ii) for satisfaction with the cumulative psychological effects of the information throughout the trip (I_{dt}^{PE}), for driver *r*, trip *t* (4.12). And, the indicators for integrated psychological effects (Y_{dt}^{PE}) can be expressed as a cumulative set of indicators for psychological effects in terms of information provision (Y_{dti}^{PE}) as expressed in (4.13).

$$Y_{dt}^{S} = \left[I_{dt}^{TE} \;\; I_{dt}^{PE} \right] \tag{4.12}$$

$$Y_{dt}^{PE} = \left[Y_{dti}^{B} \; Y_{dti}^{D} \; Y_{dti}^{E} \right]' \quad i \in I, \; \forall d, t \, , \tag{4.13}$$

where I is the total number of information provisions in trip t, for driver d. Based on the indicators for the after-trip satisfaction and for the integrated psychological effects, measurement equations for latent variables can be described as follows.

$$Y_{dt}^{S} = \Lambda_{Y}^{S} \eta_{dt}^{S} + \varepsilon_{dt}^{S} \tag{4.14}$$

$$Y_{dt}^{PE} = \Lambda_{Y}^{PE} \eta_{dt}^{PE} + \varepsilon_{dt}^{PE} \tag{4.15}$$

where η_{dt}^{S} is a latent variable for satisfaction, η_{dt}^{PE} is a latent variable for integrated psychological effects for driver r, trip t ($\eta_{dt}^{PE} = \left[\eta_{dt}^{B} \; \eta_{dt}^{D} \; \eta_{dt}^{E} \right]$), Λ_{Y}^{S} and Λ_{Y}^{PE} are matrices of factor loadings of satisfaction η_{dt}^{S} and integrated psychological effects η_{dt}^{PE} on the corresponding indicators, ε_{dt}^{S} and ε_{dt}^{PE} are vectors of measurement error in the models that are independent to each other.

Meanwhile, several propositions representing causal relations between latent variables and explanatory variables are considered to identify the latent variable structural model. Propositions 1 to 3 presented below address the causal relationships from psychological effects to satisfaction. Each of psychological effects change the level of satisfaction as it alters information-related stresses with information provision as explained previously. Propositions 4 to 6, on the other hand, are presented for the causal influences of the explanatory variables on the level of satisfaction. Specifically, Propositions 4 and 5 support the possible situations where external factors (individual attributes and travel context) are making difference in the level of satisfaction in addition to the impacts from psychological effects when the same information is provided. The last proposition addresses the effects of travel time experienced from the trip on the level of satisfaction. It is important to note that the first three propositions are only valid when the driver has received real-time information at least once in a trip.

- Proposition 1: Cognitive burden affects satisfaction.
- Proposition 2: Cognitive decisiveness affects satisfaction.
- Proposition 3: Emotional burden affects satisfaction.
- Proposition 4: Individual attributes affect satisfaction.
- Proposition 5: Travel context affects satisfaction.
- Proposition 6: Travel time experienced affects satisfaction.

In summary, the structural equation for satisfaction can be written in relation to the external explanatory variables, and latent variables for psychological effects as follows:

$$\eta_{dt}^{S} = \sum_{p} \gamma_{p}^{S} x_{p}^{d} + \sum_{q} \gamma_{q}^{S} x_{q}^{t} + \gamma_{t}^{S} t^{dt} + \mathbf{B}\eta_{dt}^{PE} + \varsigma_{dt}^{S} \tag{4.16}$$

where t^{dt} is travel time experienced by driver *d* from trip *t*, γ_{P}^{S} , γ_{q}^{S} , γ_{t}^{S} are coefficients relating explanatory variables x^{d} , x^{t} , t^{dt} respectively, to cognitive decisiveness η_{dti}^{E} for driver *r*, and trip *t*, **B** is a matrix of coefficients relating latent variables in η_{dt}^{PE} , and ς_{dt}^{S} is a vectors of structural error for η_{dt}^{S} which is independently distributed. Figure 4.3 demonstrates the modeling structure for psychological benefits (satisfaction) associated with the corresponding integrated psychological effects and explanatory variables and the incorporating indicators. In the figure, the psychological effects as integrated latent terms are inferred based on the relation to the indicators for information perception representing the psychological effects during the trip. The three integrated latent variables affect driver's satisfaction that is also identified by the indicators for satisfaction with psychological effects and for satisfaction with travel experience. To accommodate the exogenous causes of satisfaction, explanatory variables such as individual attributes, travel context, and travel time experienced are included to represent directly influences on the satisfaction.

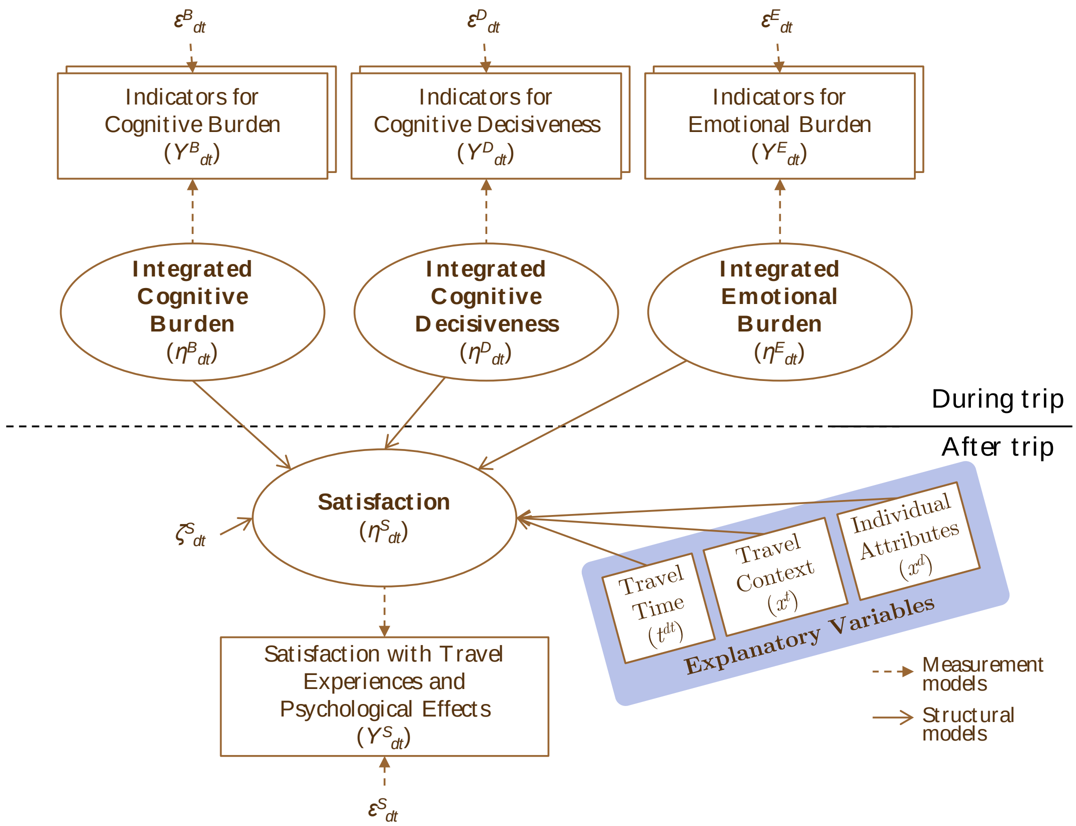

Figure 4.3 MIMIC model for the psychological benefits

CHAPTER 5. CONCLUSIONS

5.1 Summary

In this study, we have proposed an integrated modeling structure of psychological process to address drivers' subjective perception of the information and the consequential psychological effects and benefits. The proposed latent variable model for psychologocal effects is able to analytically explore the causal relationships between the latent variables that represent psychological effects from the information and the incorporating indicators that reflect driver's perception of information. Other exogenous factors such as individual attributes, travel context, and information characteristics are also included in the analysis Through this modeling we can have a better understanding of perceptional and emotional aspects of information based on different drivers, travel context and information characteristics underneath drivers' revealed route choice behavior. Another latent variable model is presented to explain psychological benefits in terms of satisfaction that includes satisfaction with both travel experience and the aforementioned psychological effects during the trip. In this broader model, we include latent psychological effect variables, i.e., cognitive burden, cognitive decisiveness, and emotional burden, in a relationship centered by a latent psychological benefit variable, satisfaction. This model helps explore the significant factors in individual driver's satisfaction that may further impact on the comprehensive value of real-time travel information.

The key contributions of this study are in demonstrating the causal relationships among the factors that construct psychological process, so that the psychological values underneath drivers' revealed behavior are explored in an explicit manner for the purpose of understanding the structure of the benefits of real-time travel information.

Accommodating the changes in information-related stresses, the explicit consideration of qualitative and psychological aspects of information process fills the gap of cognitive or perceptional assumptions in drivers' decision-making behaviors under real-time travel information provision. The propose modeling structure offers the ability to comprehend the overall benefits of real-time travel information involving explicit consideration of human psychological effect dimension, which provides a broader set of performance measures to public or private sector stakeholders relative to the evolution of the traveler information services market.

5.2 Future research directions

The analysis based on the data from the driving simulator-based experiment is still required for the model elaboration to represent drivers' behavior. In addition, potential placebo effects of real-time travel information will also be investigated to represent a specific situation where discrepancy between psychological and physical benefits exists, i.e., a case with positive psychological benefits and physical benefits below a personal threshold. In further research, the approach should be extended to quantify the inclusive benefits of real-time travel information as another concrete performance measure for ATIS.

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