Traveler Centric Trip Planning: A Situation-Aware System

by

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A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Applied Science
in
Electrical and Computer Engineering

Waterloo, Ontario, Canada, 2012

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Trip planning is a well cited problem for which various solutions have been reported in the literature. This problem has been typically addressed, to a large extent, as a shortest distance path planning problem. In some scenarios, the concept of shortest path is extended to reflect temporal objectives and/or constraints. This work takes an alternative perspective to the trip planning problem in the sense it being situation aware. Thus, allowing multitudes of traveler centric objectives and constraints, as well as aspects of the environment as they pertain to the trip and the traveler. The work in this thesis introduces TSADA (Traveler Situation Awareness and Decision Aid) system. TSADA is designed as a modular system that combines linguistic situation assessment with user-centric decision-making.

The trip planning problem is modeled as a graph G. The objective is to find a route with the minimum cost. Both hard and soft objective/attributes are incorporated. Soft objective/attributes such as safety, speed and driving comfortability are described using a linguistic framework and processed using hierarchical fuzzy inference engine. A user centric situation assessment is used to compute feasible routes and map them into route recommendation scheme: *recommended, marginally recommended*, and *not recommended*.

In this work, we introduce *traveler's doctrines* concept. This concept is proposed to make the process of situation assessment user centric by being driven by the doctrine that synthesizes the user's specific demands. Hard attributes/objectives, such as the time window and trip monitory allowances, are included in the process of determining the final decision about the trip. We present the underline mathematical formulation for this system and explain the working of the proposed system to achieve optimal performance. Results are introduced to show how the system performs under a wide range of scenarios. The thesis is concluded with a discussion on findings and recommendations for future work.

Acknowledgments

My thanks and praise go to Allah for giving me the strength, the knowledge and the determination to accomplish this work.
I would like to thank Dr. Otman Basir, my supervisor, who offered me the opportunity to be a graduate student at the University of Waterloo and gave me the guidance and inspiration to start this thesis.
I am indebted most of all to my family in Libya for their invaluable support.
I would like to thank the Libyan Ministry of Education who sponsored me during my study.

Dedication

I would like to dedicate this thesis to my parents, who started and nurtured my academic interests; to my brothers and sisters, who support and encourage me all the time.

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Chapter 1

Introduction

Trip planning is an everyday challenge for a large number of people. When a trip is planned, issues that must be considered include trip time, trip budget, and the best route that meets the demands for a particular situation. The difficulty lies in assessing the situation in the traveler environment as it pertains to his/her travel plans and objectives. Approaching trip planning as a set of independent problems, each can be tackled in isolation, can prove to be ineffective, if not deficient. For the purpose of the research presented in this thesis, the problem of trip planning is defined as determining an optimal travel path that meets traveler preferences and constraints. This chapter discusses the motivation behind tackling this problem and presents the scope of the research work conducted by the author to address this problem. The chapter is concluded by a brief summary of the thesis organization.

1.1 Motivation

The task of selecting a traveler route plays a major role in many people's daily routine. A wrong decision can be costly, in terms time, money and safety. What constitutes an optimal trip route is situation and traveler dependent. The same traveler may adjust his/her route preferences based on his/her immediate needs and the emerging travel situations in his/her surrounding. Furthermore, for a traveler, route preference criteria transcend the simple preference criteria of distance. A traveler may wish to express route quality as a mix of preferences and demands when stating his/her route goodness criteria. This may include preferences and demands such as, the route with the shortest distance, quickest route, earliest arrival time route, safest route, least expensive route, the least uncertain travel time route, the most popular route, most scenic route, etc. In [1] as many as seven factors are specified for what would determine the best route for a traveler.

Current travel aid systems, such as Personal Navigation Devices (PND's), simplify the trip routing problem to that of finding the shortest path. Such systems tend to be passive and are unable to offer the traveler means for expressing complex, and quite often, inherently conflicting criteria. Moreover, they lack the ability to enable the traveler to engage in a trade-off analytics exercise to manage conflicts among travel route criteria and demands. For example, a traveler who is racing a flight departure time may be willing to relax the importance of the financial cost criterion but at the same time may want to overstress the importance of arrival time and travel time certainty.

This thesis presents TSADA, a novel approach to trip planning. The approach accommodates both soft and hard traveler route criteria. Trip planning is addressed in two stages. In the first stage feasible routes are identified and assessed based on traveler route preferences. These route criteria are assumed to be stated by the traveler as linguistic negotiable concepts [2] [3]. A hierarchical fuzzy inference engine processes these traveler route criteria to determine feasible routes and to compute the cost of each route with respect to the stated criteria. The cost of route ranking scheme: "*Recommended*", "*Marginally Recommended*", and "*Not Recommended*".

The traveler can influence the system interpretation of what constitutes an optimal route using a “Traveler Doctrines” model. A traveler doctrine is a set of beliefs that captures the traveler’s essence of what is important and what is not that important. The second stage of TSADA is an optimization engine where the the traveler hard demands are brought into play in determining the optimal route. Hard demands are demands such as latest arrival time, maximum trip time, etc. If these demands are not satisfiable, a trip is declared infeasible [2] [3].

1.2 Scope of the Research

Trip planning has been traditionally considered as a routing problem, in which a route between two points is determined based on pre-defined criteria. This view of trip planning is no longer sound, due to the inherently increasing complexity in the traveler needs, constraints and the emerging advancements in travel means. The author takes a rather novel view of trip planning, whereby a trip plan goes beyond being of the shortest route, etc, to capture more complex traveler preferences- quantitative, linguistic, and and contextual. Such view of trip planning leads to various challenges that can only be addressed using advanced computing techniques. Techniques that can represent and process uncertainty, context, quantitative and qualitative entities, and can manage conflict. To contrive such trip planning framework the author has identified the following goals:

1. Develop an architecture of a system of modules that can capture traveler preferences, travel situation, to produce travel plans for the traveler.

2. Develop a situation assessment module that can assess the feasible routes based on the traveler’s chosen doctrine.

3. Decision aid module to produce a trip route based on the assessment made by the situation assessment module and the traveler's trip constraints.

4. Conduct experiments that show the performance of the developed system under different traffic conditions, traveler's doctrines and constraints, as well as to compare the developed system with commercial navigation system.

1.3 Organization of the Thesis

This thesis is composed of six chapters: Chapter 1 is an introduction.

Chapter 2 provides a literature review of topics related to the research, with emphasis on situation assessment and situation awareness. Situation assessment implementation techniques and frameworks are highlighted. Sensor networks and middleware approaches are reviewed as possible tools for implementing situation assessment. This chapter includes a review of the work that has been conducted with respect to decision-making in the trip-planning problem.

Chapter 3 presents the definition of the problem of trip planning. It also describes the novel Traveler Situation Awareness and Decision Aid (TSADA) framework. TSADA's internal structure is explained in detail.

Chapter 4 describes the situation assessment module. The factors used in the situation assessment are highlighted and discussed in detail along with fuzzy inference system. The chapter reports experimental work conducted to validate the situation assessment module and fuzzy inference engine.

Chapter 5 discusses the functionalities of TSADA's decision-aid module. It presents the underlying mathematical formulation for the route selection process. It also presents a proof of concept of TSADA. Experimental work to evaluate different aspects of TSADA is also reported.

Chapter 6 summarizes the research conducted for this thesis. A discussion on the work along with conclusions and suggestions for future study are also provided.

Chapter 2

Background and Literature Review

2.1 Introduction

This chapter provides literature review of various trip planning systems and algorithms. Since the framework thesis employs tools for situation assessment, sensor networks, middleware and decision aid, these tools are discussed.

2.2 Trip-Planning

Due to its inherent importance in our daily life, being individual and organizations, trip planning has been an active area of research, especially in recent years. Work on optimal trip planning goes back as early as to the Dijkstra's seminal work on the shortest path problem [4]. Dijkstra's algorithm searches for the shortest path in a graph-modulated map. Cost is associated with each link in the graph and the route with the minimum cost is the one chosen. Dijkstra's work became the basis on which many of trip planning algorithms were designed. The scope of research on trip planning has broaden to cover a wide range of problem formulations. One of these formulations is the Vehicle Routing Problem (VRP). In this problem a set of vehicles with limited capacity has to be routed in order to visit a set of customers at a minimum cost (generally the total travel time). A version of this problem imposes timing constraints, hence referred to in the literature as Vehicle Routing with Time Windows (VRPTW). This problem has received a great deal of attention [5] [6] [7].

VRPTW is a multi-objective problem as it aims to minimize the route cost and the number of vehicles. Many techniques have been proposed in the literature for solving the VRPTW problem. These techniques range from exact algorithms, such as the ones reported in [8] [9] [10], to heuristics algorithms, such as the ones based on Ant Colony and Genatic algorithms [11] [12] [13] [14] [15]. In Ant Colony algorithms, Vehicles are treated as cooperative ants that use pheromones to communicate route goodness information. Ant colony algorithms have demonstrated excellent results in addressing large scale instances of this NP-Complete problem [16]. An example of the metaheuristic techniques for the Ant colony system, is the work conducted by Ellabib et al. in [11]. They investigated the performance of the foraging model of the Ant colony system with emphasis on the initial solution techniques as well as using different desirability functions. In GAs the solution space is represented as chromosomes, and at each generation, two parents mate based on specific criteria [13]. For example, in [13] a two-phase GA approach was proposed; each chromosome represents a cluster of routes, where the first gene in the chromosome represents the first customer to be served.

Trip planning is often treated as an optimization problem similar to the traveling salesman problem (TSP). For example, the tourist trip planning problem is formulated as TSP optimization problem. In [17], Vansteenwegen et al. describe tourist trip planning as one in which tourists would like to travel from a starting point to an end point crossing specific points of interest must occur within a time constraint. This problem is called the Orienteering Problem (OP), which is similar to TSP; however, the tourist is not required to cross all points of interest.

Trip planning techniques are categorized into: Non adaptive techniques and adaptive techniques [18] [19]. In non adaptive techniques, a predefined path is chosen based on known historical, statistical, travel time information [18]. Non adaptive techniques do not rely on online information as the path from the starting to the destination is pre-defined and does not change throughout the trip [19]. In [19], Fu categorizes the adaptive trip planning systems into two types, namely, Open-loop Adaptive Rule (OAR) and Close-looped Adaptive Rule (CAR). For OAR systems, the system starts by defining a complete path from the starting point of the trip to the destination. However, the trip planner might change the predefined path each time it reaches a checking point (e.g, an intersection) based on the available online information about travel times in the network. At every checking point the system checks for a feasible route. In CAR systems, however, the trip planner does not define a path from the starting point to the destination. Instead, it checks for only the next link to travel on in the network. Fu in [19] proposes a trip planning system that uses the CAR approach. It assumes that the link's travel time is a random variable with known mean and standard deviation; it's, also, assumed that the priori knowledge about the historical traveling time is available. CAR is also used by Gao and Chabini [20]; they consider stochastic networks with travel conditions that randomly change with time.

It is quite common in these trip planning algorithms that the cost to be minimized for the optimal route is often a function of time or distance. Other factors such as safety and comfortability are not used in defining what constitutes optimal routes. Factors such as congestion is an important factor in defining an optimal route for the trip. Several solutions were proposed in the literature take this factor in consideration. In [21], Dillenburg et. al. discuss that the use of ride sharing approach as one of the methods to minimize the impact of the congestion on travelers. Ride share as described in [21] and [22] is a trip planning system in which drivers picks up traveler(s) who is/are in need of a ride, based on some proximity measures. Drivers and travelers, both, can subscribe to a trip planning service. The ride sharing can be considered as a form of an organized "*hitchhiking*." Ride sharing problem can be formulated and solved as a vehicle routing problem with budget constraints [23].

Situation assessment is an important tool by which trip planning systems can provide better solutions for the travelers.

2.3 Situation Awareness And Situation Assessment

The importance of situation assessment and awareness is evident from large number of publications on this topic. In [24], the importance of situation awareness was acknowledged, but it was determined to be an ill-defined concept. In [25], situation assessment was defined as "The process of interpreting and expressing the environment based on situation abstraction products and information from technical and doctrinal databases." In [26], Endsley defined situation awareness as "the perception of elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future." However, in [27], Endsley defined situation assessment as the process of achieving, maintaining, or acquiring a state of knowledge. Such a state of knowledge is referred to as situation awareness. Consideration to the two definitions makes it difficult to distinguish between situation assessment and situation awareness. It should be noted that the work conducted by Endsley in [26] and [27] was, in fact, a response to the statement made by Sarter in [24] that any attempt to define situation awareness is futile.

Situation assessment has been treated as both an independent research topic [28] and as a part of a larger problem (e.g., data fusion) [29] [30]. The research on situation assessment includes computational approaches along with the methodology through which such approaches can be implemented, as well as the correlation between situation assessment and the decision-making process [31]. Situation assessment implementation can be either centralized (i.e., data sent to central unit and then processed) or distributed (i.e., data processed at the sensor level [28]).

Situation assessment and decision-making have been introduced as a part of a number of data fusion models [32] [33]. The Joint Directors of Laboratories (JDL) began a project in order to define a model that can codify data fusion. In this model, the situation assessment process resides in the second level [34] of data fusion. In [35], Steinberg et al. define situation assessment with respect to the JDL data fusion model as the "estimation and prediction of relations among entities, to include force structure and cross force relations, communications and perceptual influences, physical context, etc." On the other hand, in [34], the situation assessment in the JDL model was defined as " a process by which the distributions of fixed and tracked entities are associated with environmental, doctrinal and performance data." The latter definition is indeed more informative and consistent with the definitions offered in [25] [27]. However, most reports in the literature agree that a definition situation assessment in a data fusion model is a contextual description of the surrounding environment, achieved by means of data/object aggregation.

In [36], Mixia et al. adopt Endsley's definition of situation assessment and situation awareness. However, the manner in which situation assessment is implemented is interesting. They define situation analysis as being composed of both aggregation and events correlation. Once situation analysis is completed, situation assessment can be achieved in two steps: situation classification and situation inference. A Petri net is used for correlation, and the Dempster-Shafer theory is used for situation inference. What is interesting in their work is their use of Endsley's definition of situation assessment in conjunction with their use of data aggregation to achieve a contextual description.

2.4 Situation Assessment and Awareness Implementation

In [29], Hinman lists some of the approaches for implementing situation assessment and impact assessment: Bayesian knowledge based artificial neural networks, a fuzzy logic approach, and genetic algorithm. Each of these approaches can be implemented in a variety of ways.

2.4.1 Situation Assessment using Bayesian Networks

A Bayesian network is an acyclic directed graph (DAG) in which nodes represent variables. In a DAG, variables represent finite sets of mutually exclusive states, and are connected by directed links. If a variable A is parent to a variable B, a conditional probability table $P(B/A)$ is attached [37]. They allow the user to learn about causal relationship between variables and they facilitate the use of incomplete data [38]. Bayesian networks provide a solid theoretical probabilistic work that is easily tractable [39].

In [40], Schubert and Wanielik attempt to offer a highway traffic assessment tool to aid drivers with lateral maneuvers (i.e, whether to remain in the same lane or to change lanes). Their situation assessment framework consists of two main layers. The first layer is a sensor network layer for providing front/rear lane estimation and front/rear vehicle estimation. The second layer is a Bayesian network created for situation assessment in which each recommended maneuver is implemented by many nodes at one level. The recommendations are sent to nodes in the next level where the recommended action is determined. In [40] the argument put forward to justify the use of a Bayesian network is that it deals with the uncertainty caused by the erroneous nature of sensors.

2.4.2 Situation Assessment Using a Fuzzy Inference System

Situation assessment using the fuzzy logic paradigm has received a great deal of attention in the literature [41] [42]. In [42], Chandana and Leung proposed a technique for sea surveillance using a hierarchical fuzzy logic approach in cognitive maps. This method was applied in a distributed manner at the sensor level, according to each cluster of sensors processes, the partial information it possesses in order to arrive at a local situation assessment. In this study, situation assessment was perceived as a pattern recognition problem. The work done in [42] shows the way events can be processed starting at the sensor level in order to eliminate an existing uncertainty. In [42], no indication is given with respect to how the final decision is made even though it seems that the situation assessment is considered to be the "final" decision. The terms, goal and situation assessment, are used.

The notion of team situation awareness and its relationship to individual situation awareness is an important contribution of [43]. Shu and Furuta [43]. They described a conceptual framework for team-based situation awareness. Their idea is that situation awareness is defined as the up-to-the-minute understanding of the situation in a dynamic environment. The assumption in their work is that team situation awareness can be reduced to individual situation awareness (ISA) and mutual beliefs. They devised heuristic rules to infer both the ISA and the mutual beliefs.

2.5 Overview of Multilayer Situation Assessment Models

Successful situation assessment is a multistage process, and multi-layer models for situation assessment have been proposed in the literature. In [44], Weiss et al. describe a four-layer architecture for advanced highway situation assessment. From the top down, the layers are a sensor layer, a fusion layer, an interpretation layer, and an application layer. Sensors are installed in vehicles for data perception, and these data are processed by the fusion layer in two stages: first stage by low-level fusion and second by high-level fusion, using an extended Kalman filter (EKF). The fused information is passed to the interpretation layer for situation classification. As mentioned, situation assessment can be considered a pattern-recognition problem: specific pattern features can be inferred through the fusion state in order to classify the situation. The classification process uses a fuzzy inference system (FIS) in order to infer the roadway type (e.g., expressway or other type of road). The classification can be then used to provide the assessment based on which class the situation falls into. While vehicle-based data perception is conducted locally, which minimizes communication cost and delay. However, installing sensors in a vehicle which is both costly and prone to error is a major drawback of the framework described in [44]. There is also no definition of the role of the driver in such system. A similar framework was proposed in [45].

Situation assessment has often been addressed as a contextual classification problem in the literature, and many frameworks have been designed on such basis. In [46], Springer et al. proposed a generic algorithm for situation awareness. Their model consist of three layers: a sensing layer, a feature extraction layer, and a reasoning layer. The sensing layer consists of sensors distributed in a ubiquitous order to capture raw data such as room temperature and noise level. These raw data readings are processed in the feature-extraction layer, where the data is abstracted and classified using classifiers appropriate to the type of data. For example, temperature is described as high, low,etc. A multi-step hierarchical reasoning process is then implemented in the reasoning layer, and based on the contextual knowledge, a situation awareness is inferred. In [47], Springer and Turhan describe the implementation of the work described in [46] as a four-phase procedure. The first phase is to capture the phenomena using appropriate sensors. In the second phase, a contextual description based on the sensed information. After the sensed data are described contextually, the third phase implements a reasoning process in order to arrive at a situation assessment through the use web ontology language using a description language (OWL DL). OWL is an ontology reasoning language that represents the context features in vocabularies [48]. Using these vocabularies, an inference system provides a situation assessment that describes the current situation. In the fourth and last phase, a decision is produced regarding which action to take.

The structure proposed by Schubert and Wanielik in [40] is similar to the models discussed thus far. At first, sensors capture the desired information about the environment. Next, an interpretation associates these sensory readings with a description of the geometrical features of a specific road. These geometrical features are described by statistical models. For example, two-lane estimations are represented by Gaussian distribution. Bayesian networks are then used for a probabilistic situation assessment.

In summary, three main stages are described in the literature mentioned thus far:

- Data collection: In most proposed models, sensors are used for data collection.
- Data interpretation: Collected data must be interpreted through a process of

associating the data with a descriptive form that enables the nature of data collected to be comprehended. This description might take different forms, such as linguistic or statistical. Contextual association is another form of data interpretation.

- Situation reasoning: Once a form of interpretation is provided for the data obtained, a corresponding reasoning method is needed. If the data is represented linguistically, a linguistic reasoning system would be used, such as fuzzy inference system, which is one of the best-known and most widely used linguistic inference systems). If the data are represented in a statistical form, a probabilistic model such as Bayesian network would be needed.

Because sensor networks and middleware approaches are often used for both data perception and data pre-processing, they are important components of many of the models that have been proposed and form a significant part of the research presented in this thesis. The next sections provide a brief survey of the work related to sensor networks and middleware design.

2.6 Sensor Networks

The first stage in the successful development of a situation assessment model is to identify the means by which the desired phenomena are captured within an environment. As indicated in the previous section one method of perception is to use sensors. As long as they can take measurements and present them in a detectable way, sensors can take many forms (e.g. mobile phones, radars, infrared).

Sensors have been proven to be efficient in the field of data gathering and phenomenon observation. For example, [49] describes an application in which sensors cooperate to detect road wetness, black ice, and snow. This application helps drivers decide whether a road is safe to drive on, as they are often warned about slippery road. Refrences [50] and [51] describe methods that can assist drivers in the determination of the amount of traffic and occupancy, which are beneficial in the calculation of the expected trip time.

Sensors can cooperate to exchange data and form what are known as Sensor networks (SN). SNs can be deployed over a wide area to gather different types of data, e.g., temperature, or images of the road. A wireless sensor network (WSN) allows the application to access areas without the necessity of infrastructure. WSNs are used mostly in two types of applications: monitoring and tracking [52], and they have evolved to the point where they are heavily used in both civil and military applications. If a communication model that closely follows the Open Systems Interconnection (OSI) model [53] issued, the WSN can be connected to a remote server or task manager to enable further complicated tasks.

For tasking and re-tasking, a WSN can be controlled by software called middleware. Middleware is a bridge between sensors with often small size, complex architecture and unique characteristics and high-level applications with sophisticated design developed to respond to precise demands. Middleware plays a major role in successful perception and other tasks in order to develop an accurate situation assessment as indicated in Section 2.5 (e.g. tasks such as data aggregation, data fusion, and reduction of uncertainty). A detailed description of middleware is provided in the next section.

2.7 Middleware in Sensor networks

Because of its increasing importance, middleware in sensor networks has been highlighted in recent literature. One important task that middleware performs in the applications described in this section is to provide reduction of data uncertainty. In [54], Li et al. described middleware model and proposed a confidence function based on the Dempster-Shafer method, and incorporate it into their proposed middleware architecture. Inspite of the fact that they offered no further explanation of the implementation, it should be possible for Dempster-Shafer model and other reduction of uncertainty models to be implemented with the middleware.

The use of middleware enables other tasks to be accomplished, such as data aggregation, which is useful for scenarios that requires the maximum observed occupancy or the average observed occupancy for any given road segment. TinyDB [55], Agilla [56] [57], TinyLime [58] and LEACH [59] are example of the execution of data fusion at the middleware level. In these algorithms, controlling the sensor network enables the middleware to instruct the network to perform any type of data aggregation. However, the method of interacting with the network differs from one approach to another. Agilla [57], for instance, uses mobile agents to do these tasks. Another well-known approach is MIRES [60], which uses a Publish/Subscribe (Pub/Sub) technique to enable data aggregation in a sensor network. Regardless of the method used for data aggregation, the extensive work on uncertainty reduction models and data fusion provide solid ground for suggesting that a middleware approach be used as a mandatory element for work with sensor networks, and it has hence been incorporated as an important part of the model developed through the research presented in this thesis.

The approach in [61] is a good example of how situation assessment can be implemented using a Pub/Sub technique. There are many middleware approaches based on a the Pub/Sub technique, such as the one proposed in [60].

Because middleware can be used to control sensor networks so that they can perform a variety of tasks, it is important to consider the use of middleware whenever sensor networks are being developed.

2.8 Overview of Decision Aid and the Decision Making Process

In [25], decision aid processes are defined as "Tools to enhance human decision-making performance by identifying key factors, structuring the decision process, estimating values, evaluating alternatives, predicting outcomes, effectively presenting information, or effectively managing information."

In [62] [63], Klein introduced the concept of a recognitional decision-making process and differentiated between a recognitional decision and an analytical decision. He also describes a model called recognitional primed decision (RPD). RPD depends mainly on situation assessment as a tool for arriving at a decision option. The rationale is that, with enough experience to fully recognize a situation, the first assessment of a situation will most likely be the best option for a decision. RPD was adopted as a concept model for further decision making in [45]. In [62], Klein describes an analytical decision as a process of evaluating many options in order to determine the best decision.

The decision of interest in this work was the outcome of trip planning, which is most often a route that indicates the starting and end point of the trip, with several other parameters that are associated with the trip depending on the type of trip (e.g., tourist trip or business trip).

2.9 Summary

This chapter has surveyed the topic of situation assessment from many viewpoints. The variety of definitions provided in the literature for the term situation assessment have been identified, and the difference between situation assessment and situation awareness have been explained. The definition of the decision making process has also reviewed.

Some of the methods reported in the literature for implementing both situation assessment and situation awareness have been reviewed, methods such as Bayesian networks and fuzzy inference systems.

A discussion has been included of some of the multi-layer frameworks described in the literature. These frameworks have been used to provide decision-making processes using situation assessment.

Because of their common use as a layer in a situation assessment applications, this chapter has also discussed sensor networks and middleware applications. Middleware layer was discussed as well. A variety of approaches for implementing middleware in sensor networks have been presented, as well as the various tasks that middleware can perform with respect to situation assessment.

Situation assessment has been discussed with an emphasis on trip planning, and some of the methods and algorithms for solving various trip-planning problem have been explained.

Chapter 3

Trip Planning: A Situation Aware System

3.1 Introduction

The trip-planning techniques described in Chapter 2 rely on various approaches for computing a trip that satisfies some goodness criteria, such as minimum trip cost. Generally speaking, what defines a cost function is traveler specific. Thus, it is difficult to point to any of the techniques discussed in Chapter 2 as being the best one.

In this chapter, a novel trip planning system is introduced. What distinguishes this system from existing trip-planning systems is that its notion of route cost is contextual in nature and can be constructed to reflect traveler priorities. The situation for each road segment is assessed based on specific criteria that reflect traveler preferences. If a road segment is assessed as contributing to the optimal route of the trip, it is used constructing the trip plan. The different stages, in which the traffic information is processed for trip planning, are depicted in Figure 3.2. The first stage is the data collection stage, and the last stage is the optimal route computing stage. The next section provides a formulation of the user-centric trip planning problem.

3.2 Problem Formulation

We consider a traveler X, contemplating a trip from an initial location S, to a final destination location D. The trip from S to D can be made along one of a set of feasible routes $R(S, D)$. For each route $r \in R(S, D))$ we define a set of attributes $A_r(S, D)$. A_r captures the distance, $\delta_r(S, D)$, between S and D along route r, Trip-Time $\tau_r(S, D)$ along route r, safety index $\sigma_r(S, D)$, comfort index $\phi_r(S, D)$, and traffic consistency index κ_r. Each route r is constructed as set of linked road segments

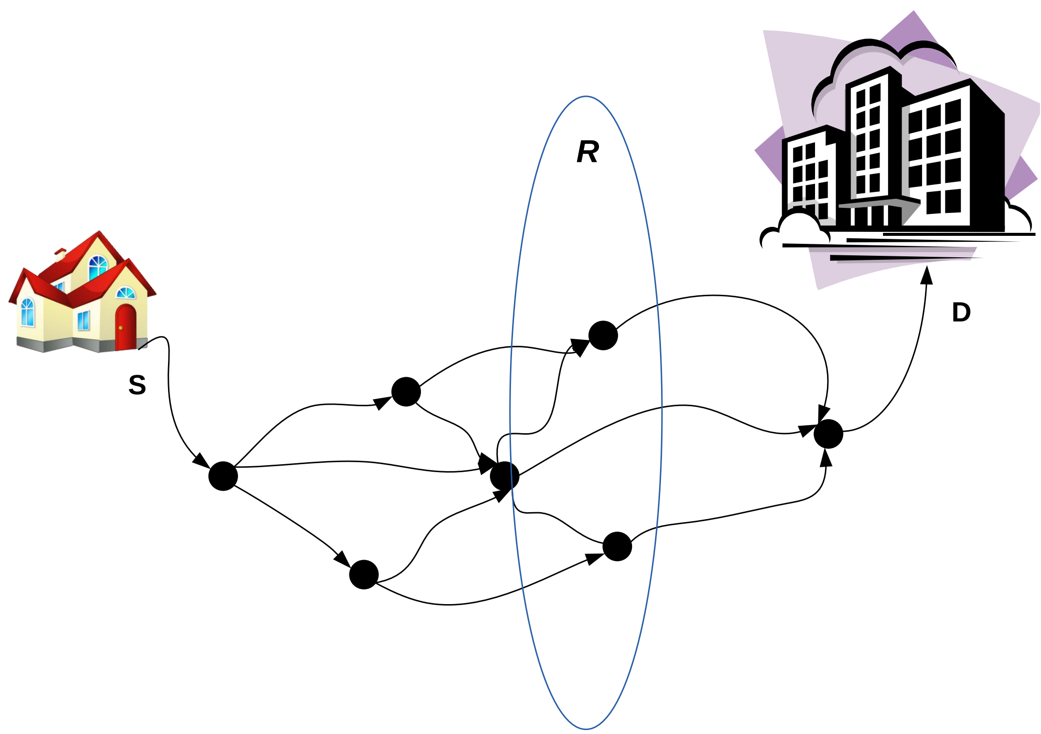


Figure 3.1: Depiction of a map from initial point S and destination point D.

$L_r = \{l_1, l_2, ..., l_n\}$, where the first road segment l_1 originates at S and the last road segment l_n terminates at D. For each road segment $l_i \in L_r$ we define $A_r^{l_i}$, a set of attributes similar to that of the route r, vis–vis, $\delta_r^{l_i}$, the travel distance along road segment l_i on route r, Trip-Time $\tau_r^{l_i}$, safety index $\sigma_r^{l_i}$, comfort index $\phi_r^{l_i}$, and traffic consistency index $\kappa_r^{l_i}$. The Trip-Time $\tau_r^{l_i}$, and safety index $\sigma_r^{l_i}$ are considered to be situation dependent, as such they are estimated based on instantaneous measurements $E(\aleph)$ provided by the sensor network $\aleph$. As will be discussed later in the thesis, this sensor network uses a number of sources to assess the situation. Under traveler X's disposal is a set of transportation means $TM = \{ tm_1, tm_2, ..., tm_m\}$. For each transportation mean tm_i and route $r \in R$ we define a cost function $\xi_r^{tm_i} = f(L_r)$.

The cost of the trip from S to D, denoted by γ, depends on the route taken, r, the transportation means used tm, and the situation pertinent to the environment surrounding the trip, e.g, traffic, weather, etc. The notion of cost in this work is multi-aspect, in the sense that it explicitly quantifies monitory costs, temporal costs, safety costs, and comfort costs, to the extent a multi-criteria cost formulation is employed to guide the trip route optimization process. Since the impact and significance of each aspect of the cost function is traveler dependent, we propose to introduce traveler preferences and constraints (i.e., *doctrine*). We denote this doctrine by $\beta_X(S,D) = \{\gamma_1, \gamma_2, ..., \gamma_p\}$, γ_i signifies a weight that traveler X assigns to a given attribute. The traveler X's desirable route can then be found as the following:

$$r_{Opt} = \underset{\forall r \in R}{Min} \Upsilon(S, D, r, A_r, \beta_X) \tag{3.1}$$

3.3 Traveler Situation Awareness and Decision Aid (TSADA) Framework

The objective of TSADA is to find an optimal route from a source S to a destination D. Routes from S to D are considered to be subject to traffic dynamics and the optimality of a given route is traveler centric, in that they are a function of traveler preferences, constraints, and demands. Figure 3.2 depicts a high level architecture of TSADA. A sensor network is employed to monitor the environment pertinent to

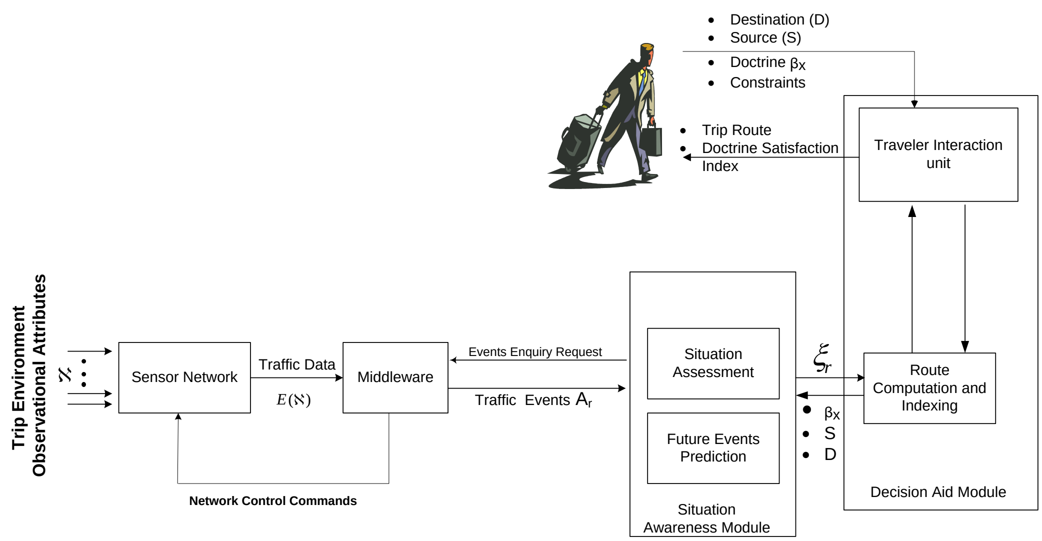


Figure 3.2: Schematic Depiction of the TSADA System.

travel conditions. This includes traffic and road conditions. Information provided by the sensor network is inherently vast, uncertain, redundant, and its relevance is traveler dependent. As such the concept of sensing in TSADA implies proper management of the sensor network so as to timely provide the necessary information to compute an optimal travel plan. Interaction between TSADA and the Sensor Network is accomplished by virtue of a middlelayer who, on one hand, acts on behalf of TSADA in presenting and managing demands to the network; and on the other hand, feeding sensory information to TSADA to facilitate situation assessment and prediction. In this work, the SN and the middleware are assumed to provide adequate information on the current and recent conditions of the roads. Snow and rain precipitation, black ice, as well as the average traffic speed and road occupancy are few examples of the information that can be obtained from the middleware layer as inputs to the situation assessment unit. *Situation Assessment* is a key component of the proposed TSADA system. Its role revolves around the processing of sensory data provided by the network of sensors that constantly supply the system with information relevant to travel. The traveler interacts with TSADA through Traveler Decision Aid module. The traveler presents his/her travel preferences, demands, and

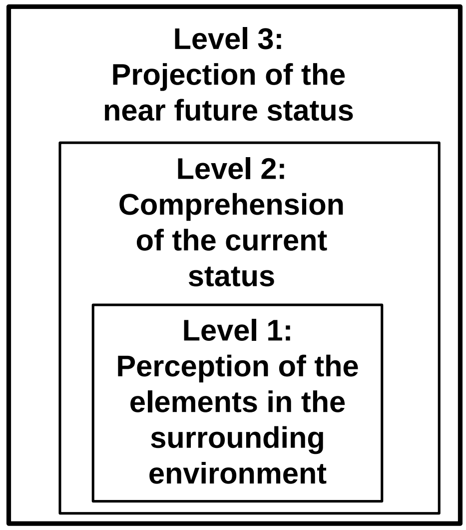


Figure 3.3: Situation Awareness Levels.

constrains to TSADA through this module, which in turn, provides the traveler with feasible routes and a recommendation scheme on such routes. The tight coupling between *Situation Assessment* and Decision Aid are discussed by many researchers. For example, in [25], situation assessment is defined as “The process of interpreting and expressing the environment based on situation abstraction products and information from technical and doctrinal data bases”, and decision aid process is defined as “Tools to enhance human decision-making performance by identifying key factors, structuring the decision process, estimating values, evaluating alternatives, predicting outcomes, effectively presenting information, or effectively managing information.”

The three stages discussed above can be described as three nested levels, Figure 3.3. The three stages stated above are the essence of TSADA. TSADA, as depicted in Figure 3.4, consists of three layers. From top-down, the first layer is the trip-planning layer. In this layer, the second and third stages of situation awareness are realized.

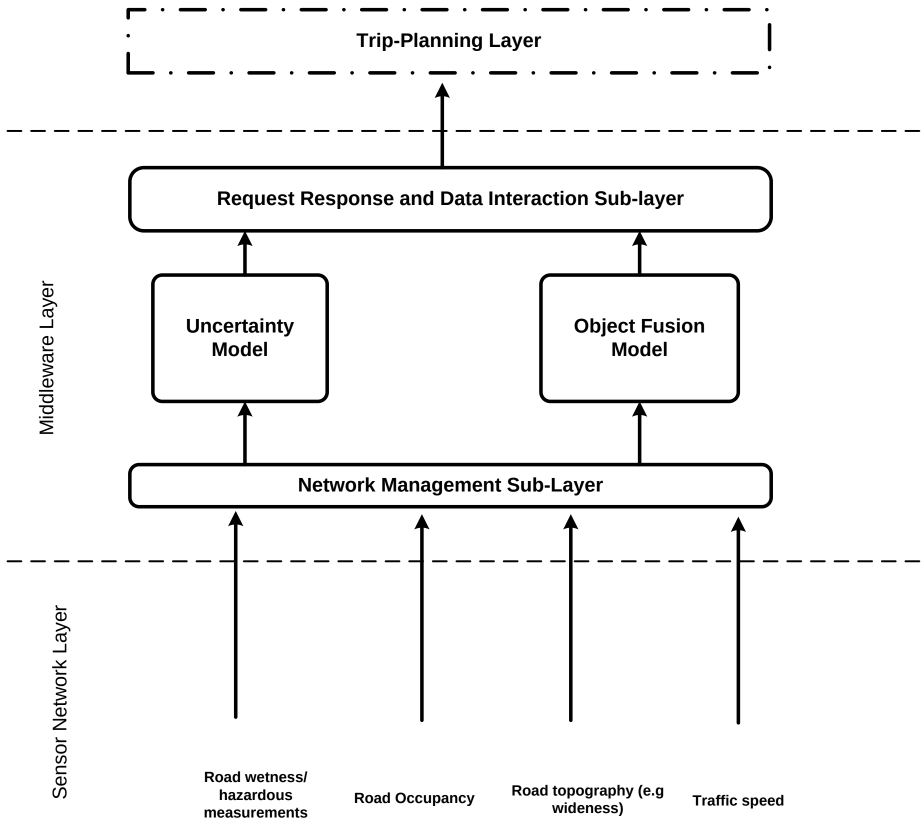


Figure 3.4: System Architecture.

The situation assessment module provides both comprehension of the current state and the projection of the future state. The second layer is the middleware layer, which manages the SN to perform tasks such as data gathering, data fetching, and data aggregation. This layer facilitates communication between the upper layer and the SN layer. The third layer is the sensor network (SN) layer. This layer is responsible for the perception of the elements in the traveler environment. The next section includes a further description of the trip-planning layer.

3.4 Trip-Planning Layer

This layer is responsible for three tasks: 1) Interaction with the traveler. 2) Execution of situation assessment on a set of feasible routes. 3) Computing the optimal route based on the traveler's preferences and constraints.

Once a demand for routing is made, the trip-planning layer defines an area of interest and performs a map-matching between the actual map the road network graph $G(V, E)$. It then sends a forecasting order, according to which specified events (i.e., Traffic attributes A_r) are fetched from that area by the middleware layer. Once the events are available, the situation assessment unit generates an assessment for each road segment. The decision is is formulated as a recommendation level, based on the cost associated with the road segments along paths on the graph. The higher the recommendation is, the lower is the cost of the the road segment. Figure 3.5 shows a description of TSADA, with emphasis on the trip-planning layer. This layer consists of several units that cooperate to arrive at a situation assessment and, subsequently, an effective decision.

A decision can be made about a route at any time instance in the future with a certain degree of fidelity based on predicted events. This is achieved through the use of predictive analytics techniques, such as neural networks, so that it is possible to predict future traffic attributes. A brief description of the components of the trip planning is as follows:

1. Event memory: In this unit, the events acquired from external sources are stored and indexed based on their type and time of occurrence.

2. Prediction unit: The provisional events are generated by this unit.

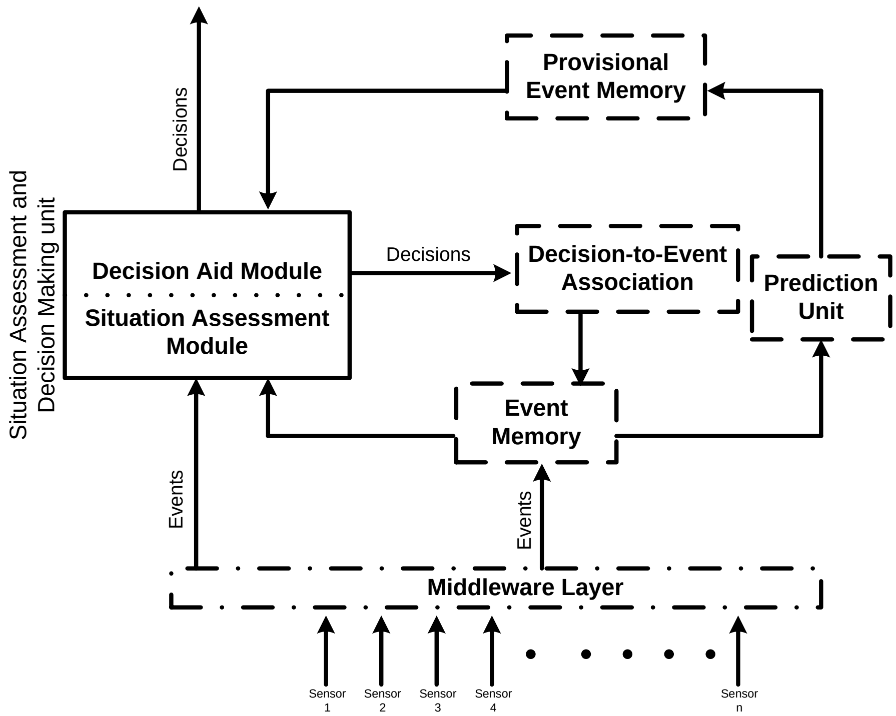


Figure 3.5: Trip-Planning Layer in the TSADA Model.

3. Provisional event memory: Events that are generated by the prediction unit are stored in this unit.

4. Decision Event association unit: Any decision, whether real-time or provisional, is attributed back to a set of events, that is stored.

5. Situation Assessment and Decision Making unit: In this unit, the events are processed according to a set of rules in order to produce a decision. A rule can be either static or dynamic. Static rules are predefined according to previous experience and knowledge of the correlation between the events and the situation assessment. Dynamic rules, on the other hand, arise when the traveler is allowed to overwrite some of the static rules with other options. However, even in this case, all options are predefined and the traveler chooses the options that

best suits him or her.

The situation awareness can be achieved by projecting the current status (i.e., the situation assessment) into the near future. The computation of this task requires a prediction unit and an event memory. One method of projecting the current state into the near future is to predict the future situation of the environment. The prediction tool should be able to use the current situation assessment to understand what the situation might be later. This feature constitutes the situation awareness module. The next section is a discussion on possible prediction techniques.

3.4.1 Prediction of Future Situations

The choice of which technique to use for event and/or situation prediction is the topic of significant research work. For example, the challenge of identifying the nature of the events whether being continuous or discrete, quantitatively or qualitatively must be addressed. Strictly speaking, two approaches could be adopted for event prediction, since the TSADA is expected to deal with a variety of events that are governed by different statistical models. These two approaches are discussed next.

3.4.1.1 One-for-All Approach

In the one-for-all approach, a single prediction model is used. The disadvantage lies in that finding a single model that fits all types of data. A statistical model cannot be used to address linguistic events, and it may not be wise to use a linguistic model for well-analyzed statistical data.

It is possible to predict what a situation might be rather than predicting the parameters that affect this situation. Using this approach renders the nature of the data becoming irrelevant. In this case, it is possible to use one model with a single tool for predicting a situation assessment. However, determining which tool to be used remains to be challenge.

Any situation assessment is a conclusion derived from many events. Because these events tend to change randomly nonlinearly, the mapping from a situation to a situation assessment is nonlinear in the set of events. For this reason, finding a good one-for-all prediction model is a hard ill-posed task.

3.4.1.2 All-for-All Approach

In all-for-all approach, a prediction of each type of data is determined based on a variety of statistical models and/or other means of prediction. For example, traffic prediction can be achieved using a fuzzy logic model, road occupancy can be predicted using a Markov chain, and so on. It should be noted that, some events, for example, to weather can be obtained from forecasting agencies. The events that result from the prediction process are used to construct a future situation for a specific time and place. This approach can be more focused than the one-for-all approach; however, it is more difficult to implement. Different prediction approaches have different types of errors. Thus, aggregating these errors and estimating and interpreting their impact on the situation assessment process needs to be addressed.

In conclusion, both approaches can be employed in TSADA on their own merits. The middleware layer that is responsible for processing sensory data for usage by the trip-planning layer is discussed in the next section.

3.5 Middleware Layer

Middleware is a software tool that is used to bridge the technical and logical gap between sensors and complex applications. It is used to facilitate the management of highly complex and ubiquitously distributed sensors regardless of the degree of heterogeneity in the network. Although the main concern addressed in this research is trip-planning, it is important to highlight briefly how the middleware layer provides accurate real-time data.

Various tasks are addressed by the middleware.

1. Aggregation: This task is the process of aggregating the data that is received from different sensors. Basic operations such as MAX, MIN, and AVERAGE are often supported by this layer [64]. One event in which aggregation can be useful is the determination of the average traffic speed. The middleware should be capable of enabling the sensor network to perform a variety of aggregation processes effectively.

2. Data uncertainty elimination model: Events communicated to the trip-planning layer are expected to be accurate. However, sensors are erroneous by nature. To overcome this problem, an uncertainty elimination model is needed in the middleware layer. Li et al. proposed a technique for minimizing uncertainty in the sensory data. The technique is based on the Dempster-Shafer paradigm [54].

3. Management sub-layer: In the process of designing a middleware layer, a need arose for a sub-layer that governs the communication between the trip-planning layer and the middleware layer. When the trip-planning layer makes a request for a specific type of event, this sub-layer serves these types of requests.

Many existing middleware systems can be used to address the above-mentioned requirements. For example, the global sensor network (GSN) and the Microsoft initiative SensorMap are both well cited in the literature [65] [66] [67]. Both systems make sensory data acquisition seamless, preventing the trip-planning system from dealing with the sensor network intricacies.

In general, when the trip-planning layer inquires about specific events, the middleware layer coordinates the communication in a way that enables the SN to satisfy the request from the situation awareness layer. The next section discusses the role of the sensor networks in TSADA.

3.6 Sensor Network Layer

For an accurate perception of the elements in an environment, an effective deployment of the SN is a necessity. When the SN is designed and deployed, critical factors such as data availability and complete coverage of the area of interest have to be determined. For the case study discussed in thesis, four types of sensors were identified:

1. Road condition probing sensors: These sensors are used to sense many phenomena including, road wetness which include the effects of snow, wet surface, and black ice. Holzwarth et al. proposed a sensing method for these features using an optical spatial frequency [49]. Their work is an example of how road condition probing can be achieved.

2. Road occupancy and traffic monitoring: Road sensors can capture images of the road in order to determine occupancy. Inductive loop sensor can be used to calculate road occupancy [68].

3. Vehicle speed detection sensors: Different approaches can be used for estimating the speed on a specific road. Some of these approaches, such as radars, are expensive, while others, such as inductive loop sensors, are quite inexpensive (Figure 3.6) [68].

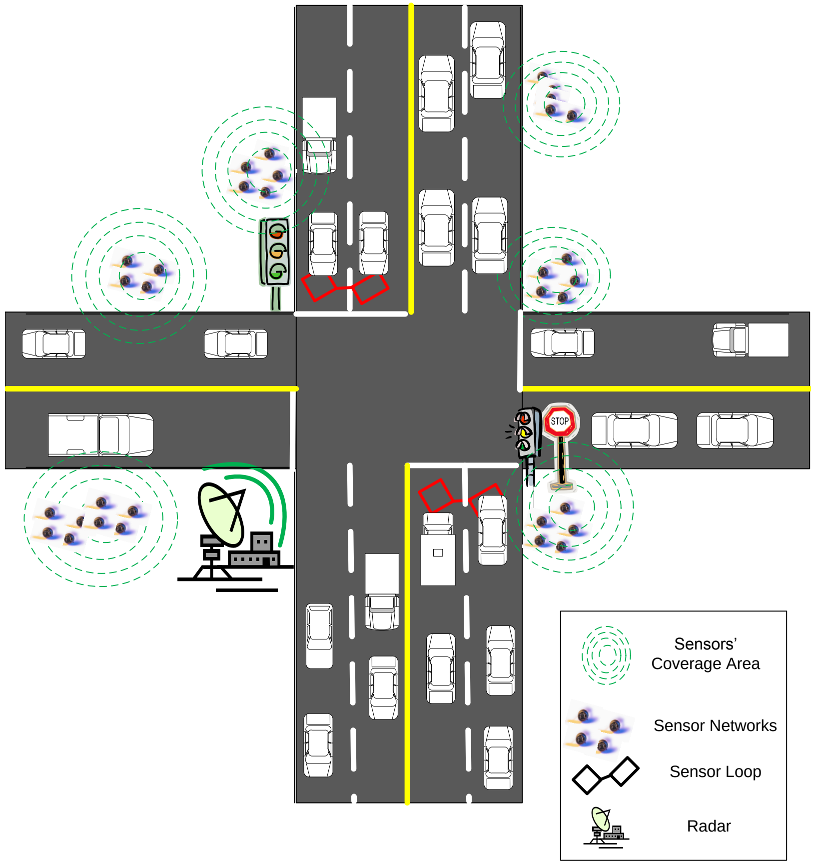


Figure 3.6: Sensor Network for Vehicle Routing Applications.

4. Road topography recognition: Road width and surface condition (e.g., hazardous, smooth, or unpaved) are major factors in determining the safety of the road. Several types of sensors can be used for the recognition process. Infrared sensors detect any change in the shape of the surface. The results from imagery sensors can be compared with the results stored database of a GIS model, which provides a relatively good estimation of the road topography conditions.

The deployment of SNs is beyond the scope of this research. It is important, however, to stress that object level data fusion, data aggregation, and other data processing techniques within SNs must be supported at the middleware layer. Indeed, compatibility between the SN layer and the middleware layer is most certainly an important factor that affects the success of TSADA.

3.7 Summary

This chapter has described a novel traveler centric trip-planning system, named Traveler Situation Awareness and Decision Aid (TSADA). The aim of this system is to utilize an understanding of the current situation on specific road networks in order to produce a decision about the best route for a travelers. This system overcomes the shortcomings of traditional trip-planning systems. Shortcomings such as the significant difference between the expected average speed and the actual average speed; in TSADA, it is possible to determine the average speed in real time as they are provided by traffic speed sensors. Central to the operation of the developed system is the effectiveness of the situation assessment module, and the fact that the information based on which the situation assessment module performs its tasks in real-time.

All three layers are equally critical for the success of TSADA. The next chapter describes both design of the situation assessment module, as well as reports experimental results that demonstrate various aspects of the situation assessment module.

Chapter 4

Fuzzy Based Situation Assessment

4.1 Introduction

The route selection problem is a function of a number of parameters, based on which roads are assessed with respect to traveler preferences, objectives and constraints (criteria). The assessed roads may constitute the most effective route (i.e., decision) according to the traveler's specific criteria. Thus, two aspects need to be tackled in order to achieve the ultimate goal of route selection, namely, the assessment of the road network situation and the selection of the traveler optimal route. Situation assessment provides the decision making module with the appropriate understanding of the current situation.

This chapter describes the situation assessment module. The factors used in the situation assessment are highlighted and discussed in detail along with fuzzy inference system. The chapter reports experimental work conducted to validate the situation assessment module and fuzzy inference engine.

4.2 Situation Assessment in TSADA

Situation awareness is a three-stage activity. The first stage is the perception of the status, attributes, and dynamics of relevant elements in the environment. In the context of travel, this may include weather, traffic flow, road closure, etc. The second stage is the comprehension and the understanding of the significance of those elements in light of the traveler's goals. Once the environmental elements are assembled together to formulate a holistic picture of the environment and an appreciation of the significance of information and events, a mental picture of the current situation is formed. For example, as the traveler progresses on a route towards a destination at a given point in the time, an accident occurs in his/her vicinity and the traffic is developing to a rush-hour condition, and the weather is such that side roads are quite slippery. The third stage is the projection of future events, short term and long term. For this to occur, comprehensible knowledge of the status and dynamics of the elements, and a comprehension of the situation perceptually and contextually must be performed. This enables the system to help the traveler make the right decisions, based not only on the current situation but what is anticipated. For example, based on an incident occurrence in a given point on the route, the system predicts the eventuality of this incident and how its effect propagates temporally and spatially. In [69], Endsley and Rodgers discuss situation assessment and situation awareness. They maintain that event prediction is a key difference in distinguishing situation assessment from situation awareness.

It is worth highlighting the distinction between the process of situation assessment and the process of decision making. Decisions can be categorized as either an actional, or a non-actional decisions. Actional decisions are decision about an action to be taken. For example, a decision to drive on a road is considered to be actional decision.

A non-actional decision is a decision that does not give rise to an action. In this sense, situation assessment can be considered a non-actional decision.

The distinction can be made clearer by specifying two further types of decisions: *recognitional* and *analytical*, as discussed in Chapter 2. A *recognitional* decision is one about an observation and is made based on previous experience that the decision maker possesses and trusts. A situation assessment made based on experience can be considered a *recognitional* decision. One might argue that rather than differentiating between the situation assessment and the decision that is to be made, the discrepancy is between the situation assessment and the decision-making process, and this discrepancy can be understood by stating that the decision-making is considered in this research as an actional decision. Actional decision is one that demand an action, and situation assessment is a decision that does not demand an action.

Central to road situation assessment are the preferences of the traveler as they pertain to travel routes. These preferences may span various aspects, for example, safety, speed, or a combination of both. Integration of these pieces of information, including traveler's preferences and road conditions, the system will perform a traveler-centric assessment so as to produce a recommendation scheme on feasible routes. This process can be computationally intractable if we are to employ traditional crisp computing approaches. Therefore, we chose to use soft computing whereby the inputs to the situation assessment process, as well as the underling mapping from the situation state to the a decision recommendation, are represented as linguistic/Fuzzy concepts.

The traveler's factors used in this work that result in a road being recommended as a possible candidate for route selecting are road safety, the average traffic speed, and road congestion.

4.2.1 Road Safety

Safety is an interesting factor that travelers might be considering. Some travelers might think that it is better to be safe than sorry. To determine whether a trip is safe, the decision maker needs to know what is happening and/or about to happen on the roads. However, effectively incorporating the consideration of safety into the system requires a definition of road safety. Road safety, $\sigma_r(S, D)$, can be defined as the minimized safety risk involved in the use of a specific road r. However, risk for drivers can be the result of many factors. For example, roads with high accident rates are generally considered risky; driving areas were cellular coverage is lacking can also be viewed as risky. In addition, some drivers may take into account the weather condition as a possible source of risk.

For the experimental work conducted in this research, road safety index, $\sigma_r(S, D)$, is defined according to the following factors: the presence or absence of black ice, the amount of snow on the road, and the number of lanes defining the road. These factors are chosen for determining whether a road is safe. It is important to draw a clear distinction between the road safety index $\sigma_r(S, D)$, and the trip safety as it pertains to the *safety* doctrine as explained later in this chapter.

4.2.2 Average Traffic Speed

Average speed, $S_{average}$, is the speed required for a vehicle to cross a distance d in an average time of t_{avg}. This expected average speed can be calculated in a number of ways. For simplicity, it is assumed that the detected traffic speed is equal to the average speed $S_{average}$. In TSADA, the average speed $S_{avgerage}$ is updated so that Equation 4.1 is satisfied. When Equation 4.1 is satisfied, it is possible to estimate the actual arrival time and thus also possible to choose a route with a satisfactory overall trip time.

$$S_{average} - S_{actual} \approx 0 \tag{4.1}$$

4.2.3 Road Congestion

Road congestion is an important factor in trip planning because most travelers would like to avoid congestion. Congestion can also affect trip safety. Wang et al. stated in [70] and [71] that although road congestion has no apparent relationship with the frequency of accidents on a specific road, increased road congestion is associated with fatal and serious injury accidents. Congestion will also affect the average speed. For these reasons, road congestion is considered as an important factor to be incorporated in the trip planning.

4.3 Situation Assessment Using Fuzzy Inferencing

In this thesis, the fuzzy inference system represents the experience based on which a situation assessment is made [62] [63]. It is possible to refer to the situation assessment as a *recognitional* decision, as decision is produced with respect to how well the road is recommended. Thus, the output of the fuzzy inferencing engine can be viewed as recognitical (recognitional and analytical) decision. Human experience and knowledge are captured in this engine in the form of membership functions and rules. The recognitional aspect of the fuzzy inference engine can be attributed to the engine's rule-base, while the analytical aspect can be attributed to the defuzzification proocess which maps the engine state assessment to a non-actional decision.

As shown in Figure 4.1, the situation assessment is divided a into three main stages:

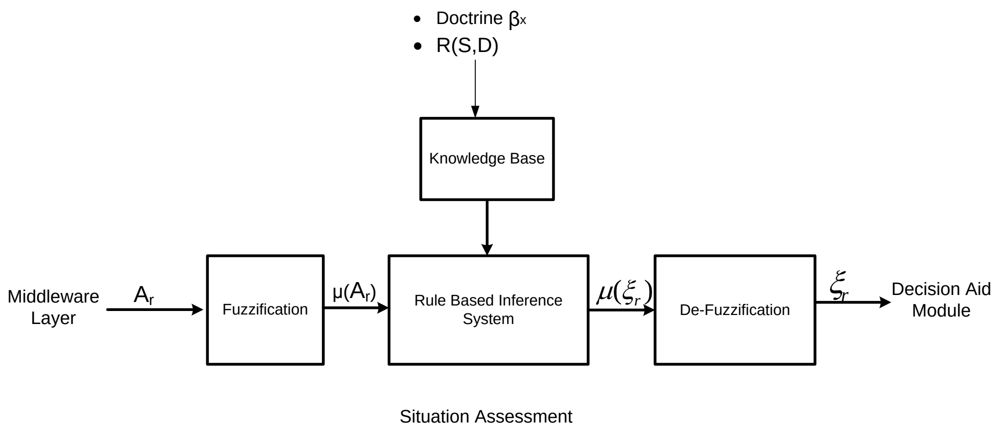


Figure 4.1: Inner Schematic of the Situation Assessment Process.

- Fuzzification: Traffic attributes, A_r, of a route r are assigned a membership function, μ_{A_r}. The definition and ranges of the fuzzy sets assigned to the traffic attributes, A_r, are shown in Table 4.1. Unfortunately, no conventional method can guarantee that the membership functions chosen is correct. In this research, the membership functions employed by the inferencing engine are chosen heuristically, based on a trial and error.

- Inference rules: Here, a decision about whether the road is to be recommended is based on specific rules derived from the knowledge-base at hand. The result is presented in a fuzzy logic membership function. The inference engine is based on the Mamdani model, which is probably the most common inference system due to its simplicity. The Mamdani model uses the following form of inference rules:

$$IF\ x_1\ is\ X_1\ AND\ ....x_i\ is\ X_i\ ....\ AND\ x_n\ is\ X_n\ THEN\ y\ is\ Y. \tag{4.2}$$

where X_i's and Y represent the Fuzzy sets. "x_i is X_i" means that the value of the variable x_i belongs to the fuzzy set X_i [72]. The Mamdani model, as shown

Table 4.1: Fuzzification Scheme.

Feature	Range	Member Function
Road Occupancy	0 - 100%	1- Open 2- Moderate 3- High load 4- Extremely high
Road Width	0 - 12 m	1- Narrow 2- Medium 3- Wide
Congestion	0 - 100%	1- Wide Open Road 2- Moderate Congestion 3- Heavy Congestion 4- Stop and Go
Degree of Snow	0 - 1	1- No snow 2- Light snow 3- Heavy snow
Black Ice	0 or 1	1- No black ice 2- Black ice
Average Speed	0 - 120 Km/hr	1- slow 2-Medium 3- Fast
Safety	0 - 1	1- Safe 2- Careful 3- Unsafe
Road Recommendation Level(FIS output)	0 - 1	1- Recommended 2- Marginally Recommended 3- Not Recommended

in Figure 4.4, uses the following implication for Equation 4.2:

$$\mu_Y(y) = \min\left\{\mu_{X_1}(x_1), ..., \mu_{X_i}(x_i), ..., \mu_{X_n}(x_n)\right\} \tag{4.3}$$

- Defuzzification: The output of the situation assessment (i.e., the road recommendation level) must be a crisp value for further processing. To produce an output with a crisp value, two defuzzification techniques are used:

  1. Centroid method: In this method, a calculation is made for the centroid, also known as the center of gravity (COG) [73] for the area under the mem-

bership function. The calculation determines the position when both the right and left moments are equal [74]. The centroid method is calculated as follows:

$$\xi = \frac{\int_x \mu_R(x) x dx}{\int_x \mu_R(x) dx} \tag{4.4}$$

2. Mean of maximum (MoM): In this method, ξ is the average of the output values with the highest degree of possibility ξ [75].

$$\xi = \sum_{i=1}^{M} \frac{m_i}{M}, \quad m_i \in \xi \tag{4.5}$$

- Knowledge-base: The knowledge-base or expert-base, is an important factor for forming the rules on which a decision can be made about a particular situation. A robust knowledge about the traffic attributes and how they contribute positively or negatively to produce a good travel conditions must be presented, in order for the situation assessment to be accurate and precise. Knowledge systems might take several forms. One is a software package that includes information that may later simulate human experience.

4.3.1 Hierarchical Fuzzy Inference Engine

The overall situation assessment was implemented in a hierarchical fuzzy formulation. The main reason behind this choice was the need to accommodate traveler preferences. Traveler preferences are related to the assessment of the traffic attributes and weather conditions. For example, the safety index $\sigma_r(S, D)$ is computed from two factors: snow and black ice on a periodical basis. On the other hand, the assessment of the average speed index $S_{average}$ is a time-variant event-driven process. Congestion index assessment can be considered a time-variant process as well. These indices are not computed at the same time as the condition affecting them are changing on different time basis. Furthermore, the road recommendation assessment is computed based on these three indices. Thus, it can be seen that it is best to decompose the assessment into two levels. From top-down, the first level is the recommendation assessment level, and the second level is preferences' assessment level in which these three indices are computed. These two levels are depicted in Figure 4.2 as the following:

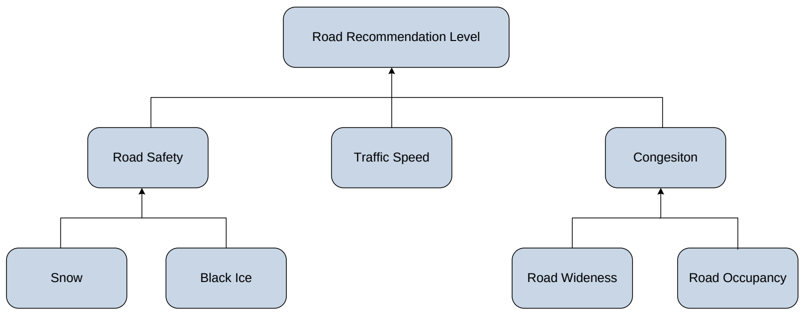


Figure 4.2: The hierarchical order in the situation assessment module.

- Level one: at the this level, a situation assessment, ξ_r, is produced in order to determine the situation on a specific road r with respect to safety and traffic congestion. The safety situation assessment for a specific road is inferred from knowledge obtained about the current road conditions with respect to both black ice and snow. Congestion is assessed based on information obtained about the width of the road and car occupancy.

- Level two: at this level, trip safety index $\sigma_r(S, D)$, road congestion and the average speed index $S_{average}$; along the travel path are used as inputs to situation assessment of the road recommendation level. This process is conducted for all targeted road segments.

4.3.2 Implementation of the Hierarchical Situation Assessment

As mentioned, the situation assessment module in TSADA is based on a hierarchical approach. The inference rules for the situation assessment use the three discussed factors: *safety*, *average speed*, and *congestion*.

The process of arriving at recommendation about the road, as shown in Figure 4.2, is conducted as follows: an assessment is first made about whether a road segment is safe or not. Another assessment is also made about the level of congestion on the same road segment. These two assessments are then combined with an assessment of the average speed in order to reach a final assessment about recommendation level for the road segment under consideration.

Safety assessment is based on two factors, the presence or absence of black ice and the amount of snow on the road. The following inference rules are an example of the process by which the overall safety assessment is produced in the safety inference system.

```
IF IsNoBlackIce & IsNoSnow
    Then IsSafe


IF IsLightSnow & IsNoBlackIce
    Then IsSafeWithCaution


IF &IsHeavySnow&IsBlackIce
    Then IsUnsafe
```

The level of congestion on the road, on the other hand, is determined by reasoning road occupancy and the number of lanes in each road. The number of lanes is translated in width which is measured in distance units. The following rules show how congestion can be assessed based on the information available regarding road occupancy and road width.

```
IF IsNarrowWideness & IsLowOccupancy
    Then IsNoCongestion

IF IsWideWideness & IsModerateOccupancy
    Then IsModeratCongestion

IF IsExtrHighOccupancy
    Then IsStpGoCongestion
```

Once the situation assessment has been completed with respect to safety and traffic congestion, the overall situation assessment can be realized. The following inference rules show how the situation assessment is hierarchically derived.

```
IF IsSpeedLow & IsUnSafe & IsHeavyCongestion
    Then NotRecommendedRoad
```

The rule above is a general rule that describes the overall recommendation based on the assessment of road *congestion*, *safety* and the *average speed*. However, TSADA employ three doctrines to ensure that the assessment process is traveler-centric. In this case, different travelers will end up with different situation assessments; and ultimately different trip plans, even if the travelers have identical start and destination addresses- a faculty that distinguishes TSADA from other trip planning systems. The next section explains the doctrines used in the TSADA system.

4.4 TSADA System's Doctrines

Situation assessment systems tend to use a type of doctrine in the comprehension stage provide references to support this statement. In our case, traveler doctrine, β_x, is a set of beliefs based on which the situation assessment module perceives the environment. This perception doctrine determines the way in which the situation is assessed: negatively or positively.

Three doctrines are offered to the traveler as an initial option. The first doctrine gives priority to safety: if the road is safe then it is recommended, this doctrine is referred to the *safety* doctrine. In this doctrine the highest weight, γ_i, is given to the safety index $\sigma_r(S, D)$. For simplicity, we define safety in terms of weather conditions that may complicate driving and as a result compromise the safety of the travelers. The second doctrine is the *speed* doctrine: the road in which the actual average speed is high is recommended. In *speed* doctrine the highest weight γ_i is assigned to the average speed, $S_{average}$. The third doctrine is the combination of safety and speed, i.e., the *compound* doctrine. Both preferences are considered simultaneously, and the aim is to find a point of compromise. At that point if speed and safety are relatively satisfied then the road is recommended. The use of fuzzy inference engine enables us to take full advantage of human experience so as to support these three doctrines simultaneously.

4.4.1 Speed Doctrine

When using the *speed* doctrine, TSADA follows the doctrine "If the route is fast enough, we might arrive early." The most important aspect of the *speed* doctrine is the average speed on a road segment,$S_{average}$. If the average speed is slow, then this road is *not recommended*. This condition is represented as follows:

```
IF IsSpeedLow
    Then NotRecommendedRoad
```

The membership functions representing the average speed fuzzy sets are depicted in Figure 4.3

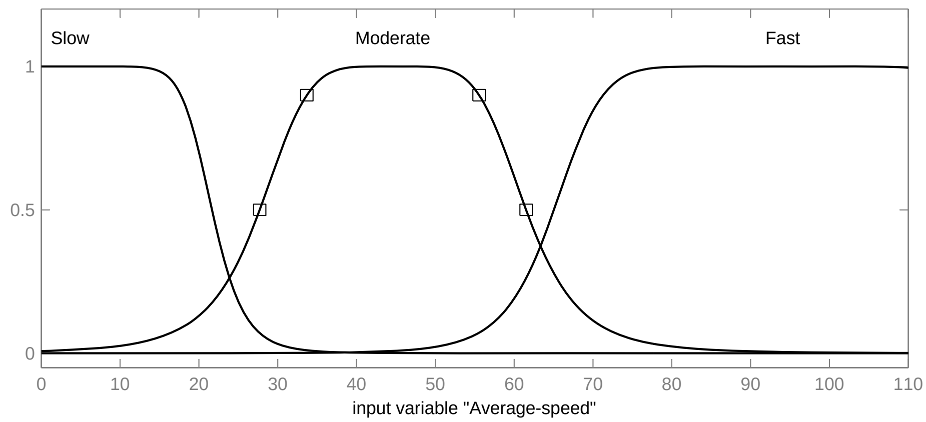


Figure 4.3: Membership functions for average speed in the TSADA system.

Giving the highest priority to the average speed does not mean neglecting other trip planning factors. Factors such as traffic congestion are also considered when the road recommendation level is assessed in the speed doctrine. If the speed is moderate, it is important that the level of traffic congestion be checked. If the traffic congestion is heavy, then the road is *not recommended* because of the possibility that the speed will slow down. The following rule shows this relationship:

```
IF IsSpeedLow & IsSafeRoad & IsHeavyCongestion
    Then NotRecommendedRoad
```

The safety of the road is considered when the road recommendation level is assessed. This assessment it being conducted based on the fact that all factors must be considered. However, the weight given to a factor differs based on the doctrine on which

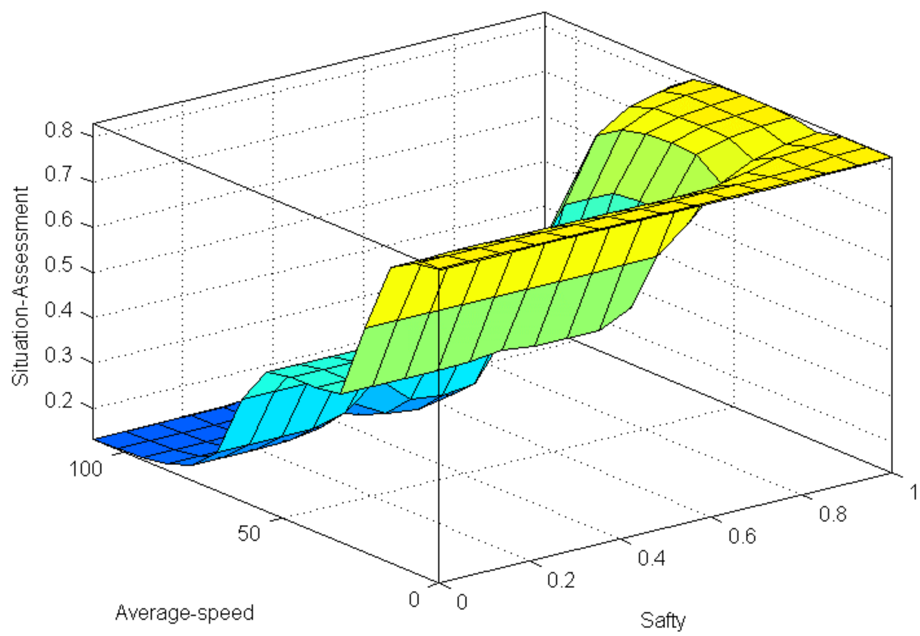


Figure 4.4: Surface Based on the Mamdani Implication Rule for the Average Speed Doctrine.

TSADA is operating under. For the *speed* doctrine, the average speed, $S_{average}$ has a higher priority,γ_i, than other factors.

4.4.2 Safety Doctrine

In the *safety* doctrine, the road safety index, $\sigma_r(S, D)$, is assigned the highest weight among the other preferences of the traveler. When the *safety* doctrine is being used, safety is the most important factor. The following rule leads to a recommendation against the use of any road that is not safe:

```
IF IsUnSafe
    Then NotRecommendedRoad
```

Other factors such as speed and congestion, are not ignored, and in fact are rather well considered in this doctrine. For instance, the following rule shows that for a road that has a moderate safety assessment can be labeled as *not recommended* if both speed and congestion are considered poor:

```
IF IsSpeedLow & IsSafeWithCaution & IsHeavyCongestion
    Then NotRecommendedRoad
```

For the same safety factor with better speed and congestion condition, the road is *recommended*.

```
IF IsSpeedSufficient & IsSafeWithCaution & IsNoCongestion
    Then RecommendTheRoad
```

The experience on which these rules are based differs from one system to another as one person's perspective differs from another. What one person considers to be safe another may think of it as risky. A robust set of rules is therefore needed when a general understanding of safety and risk is required. For this work, a set of rules were devised for the fuzzy inference engine in which toad safety factors were defined by fuzzy logic sets. Road safety is described by a fuzzy set of membership functions as shown in Figure 4.5. Another factor that affects trip safety is traffic congestion, which is also represented by a fuzzy set, the elements of which are described by the membership functions shown in Figure 4.6.

4.4.3 Compound Doctrine

The *compound* doctrine follows the doctrine "Get me there as fast as possible if the road is safe." In this doctrine a negotiation is conducted between safety and speed in order to determine a middle ground. For the *compound* doctrine, the following rules show how one can reason about both the safety index, $\sigma_r(S, D)$, and the speed index,

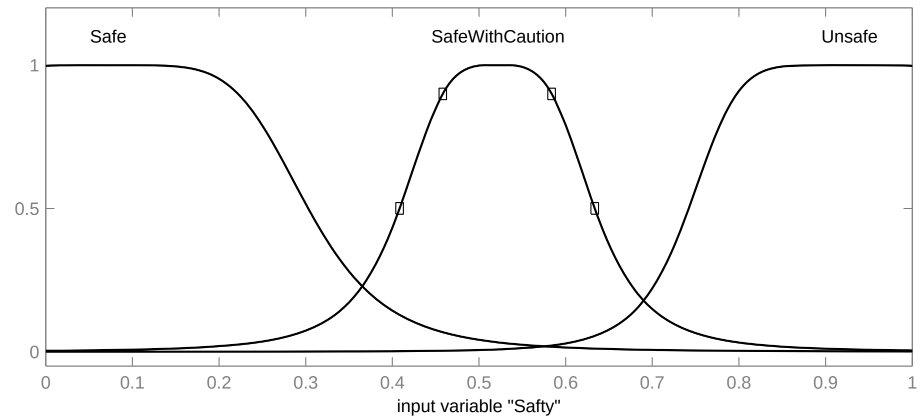


Figure 4.5: Membership Functions for Safety Index in the TSADA system.

$S_{average}$, in order to find a recommendation on the road segment under consideration.

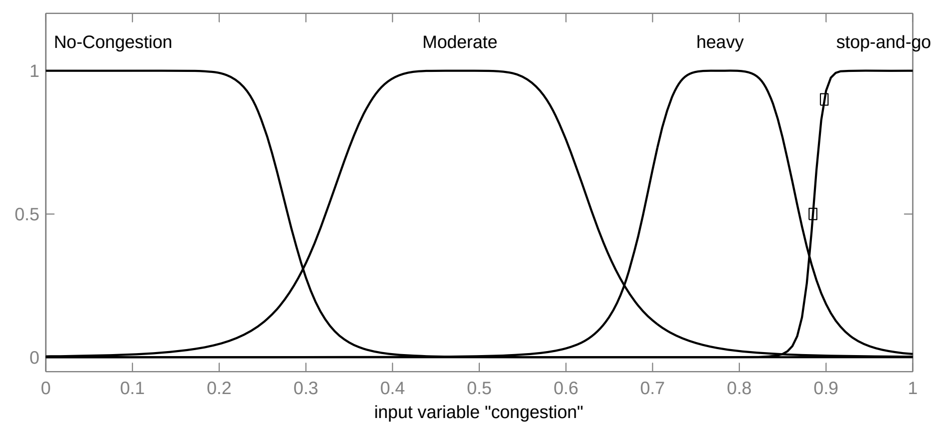


Figure 4.6: Membership Functions For Congestion in TSADA system.

It can be seen that, in this doctrine, equal weights γ_i's are given to the speed and safety index attributes; while lower weights are assigned to the other attributes. Traffic congestion also has an effect on the situation assessment and the resulting road recommendation. Roads with high congestion may give rise to safety concerns, and road congestion also has a number of degrees represented by fuzzy logic sets, as shown in Figure 4.6.

The fuzzy inference rules that deal with these factors are designed so as to handle the *compound* doctrine. A comparison of Figure 4.8 with Figure 4.4 and Figure 4.7 reveals that the compound doctrine has implications beyond the safety and average speed doctrines. This difference is attributable to the rules according to which safety and speed are considered under in the final result. For the *compound* doctrine the

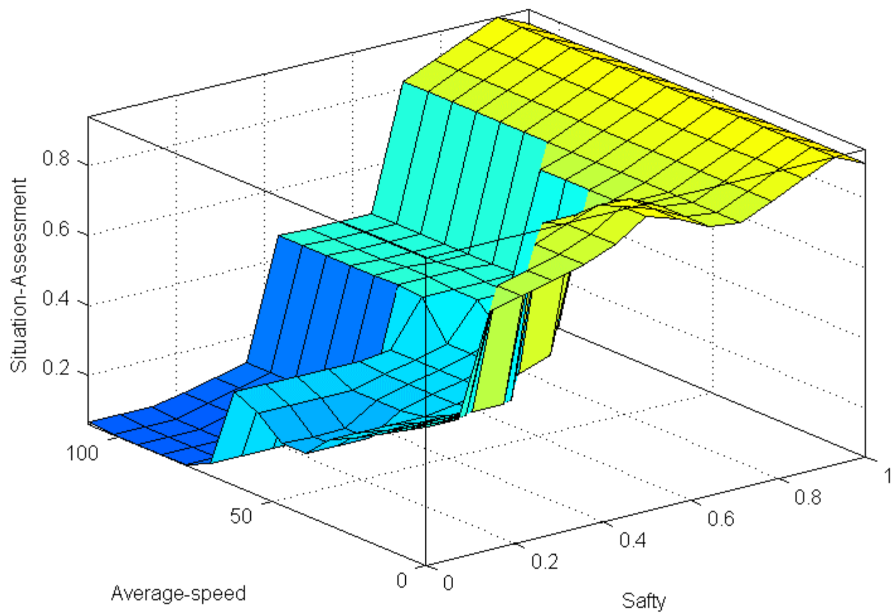


Figure 4.7: Surface Based on the Mamdani Implication Rule for Safety in the TSADA system.

following rules show how both safety and speed are considered in order to obtain a recommendation level of the road segment under review:

```
IF IsSafeRoad & IsSpeedSufficient & IsNoCongestion
    Then RecommendTheRoad
```

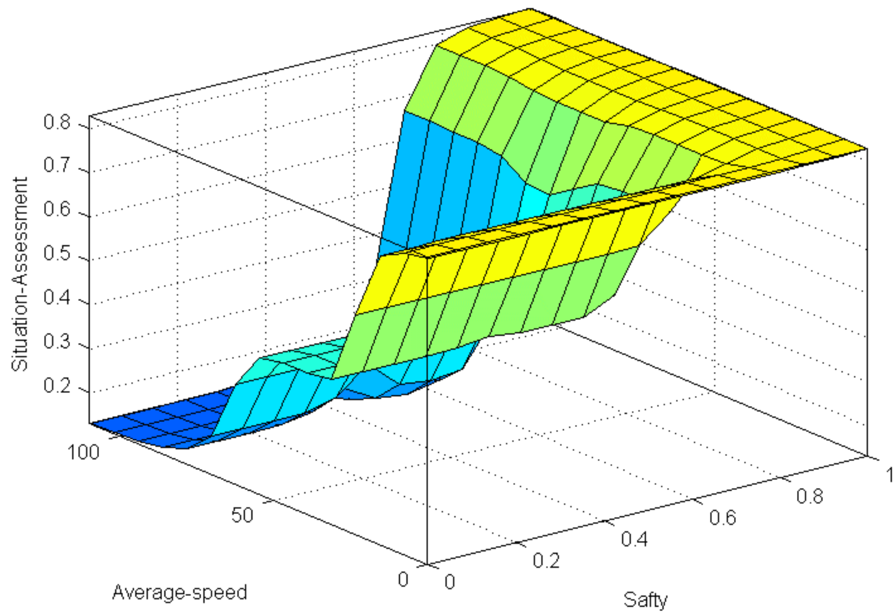


Figure 4.8: Surface Based on the Mamdani Implication Rule for the Compound Doctrine.

```
IF IsSpeedLow
    Then NotRecommendedRoad


IF IsUnSafe
    Then NotRecommendedRoad
```

The next section describes the experimental work conducted in order to show how the three doctrines differs in assessing the same situation.

4.5 Experimental Work On Situation Assessment using Fuzzy Inference System

For the purpose of proving the efficiency of TSADA a hierarchical fuzzy inference system (FIS) is constructed according to the schematic shown in Figure 4.2. The hierarchical FIS in TSADA consists of the following sub-FIS's: a congestion assessment FIS; a safety Assessment FIS; and a recommendation-level assessment FIS, in which the recommendation-level FIS resides in the top level of the hierarchical FIS. The recommendation-level assessment FIS is designed to be able to switch among three doctrines: the safety-based FIS, speed-based FIS, and compound-based FIS. These three modes are explained in Section 4.4. A total of 57 rules are devised and implemented in support of the experimental work.

Two examples are provided in this section: the first example presented in this section is on the implementation of safety-centric TSADA in order to provide an explanation on the safety assessment process. The second example is constructed as such all the three doctrines described in Section 4.4 are implemented and compared. These two examples are meant to provide a better understanding of the process by which the situation assessment operates in TSADA.

4.5.1 Road Safety Assessment

Figure 4.9 shows the crisp value given to represent the presence of snow on a specific road. The membership functions representing snow are shown in Figure 4.10. The black ice, in this example, is determined to be essentially nonexistent. As shown in Figure 4.9, a set of seven rules are used to assess safety on the road. Each rule will result in a different safety assessment, all of which are combined together to conclude the final safety assessment of the road. The assessment of road safety falls into the

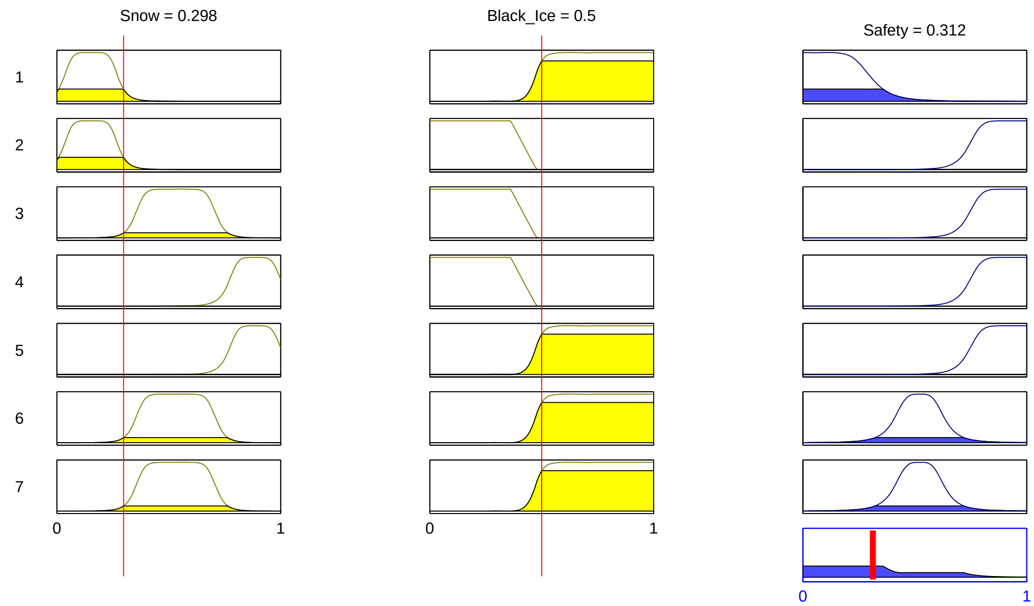


Figure 4.9: Fuzzy Inference System For Road Safety Assessment .

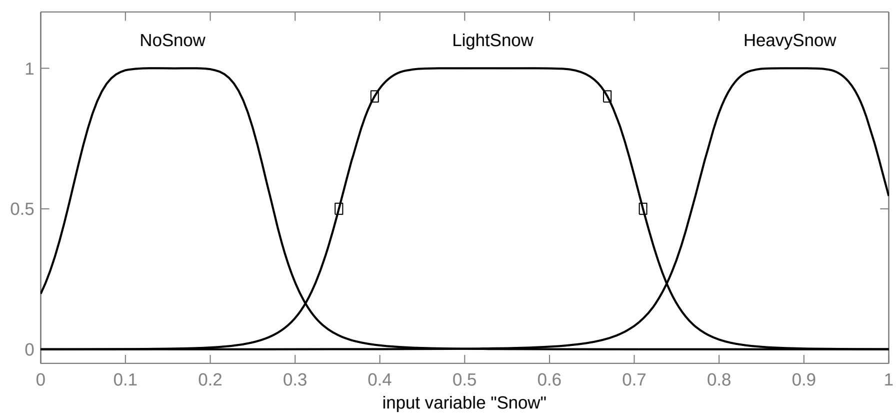


Figure 4.10: Membership Functions Representing the Amount of Snow on the Feasible Routes.

area between the “road is safe” and “the road is safe with caution”. Due to the operation of the centroid defuzzification method, the final result is that the road is safe.

In the next section, the second example is implemented to demonstrate how each of the proposed doctrines produces a different situation assessment under the same situation. The road recommendation level is represented by the membership functions shown in Figure 4.11.

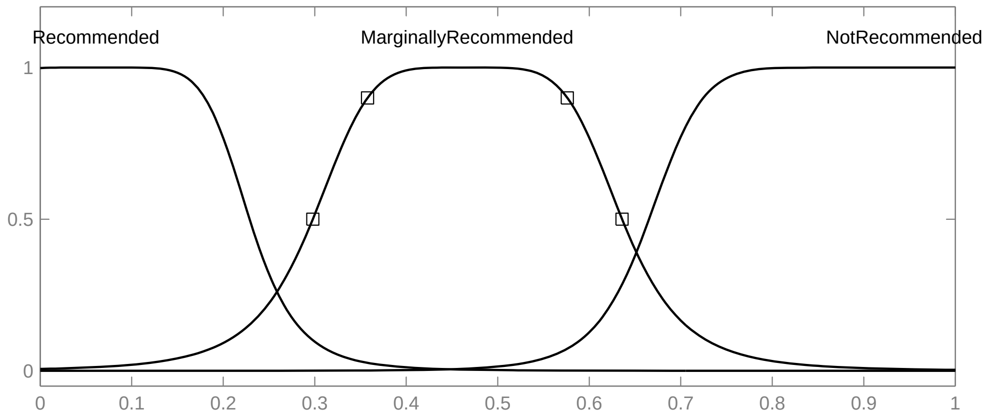
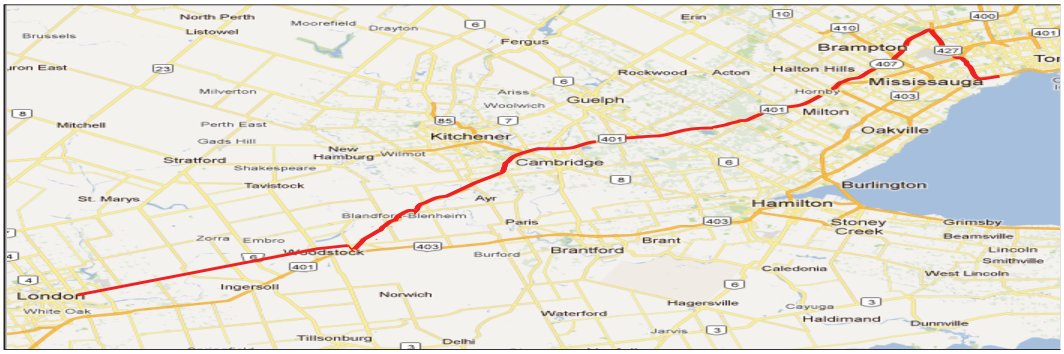


Figure 4.11: Membership Functions For Road Recommendation in TSADA system.

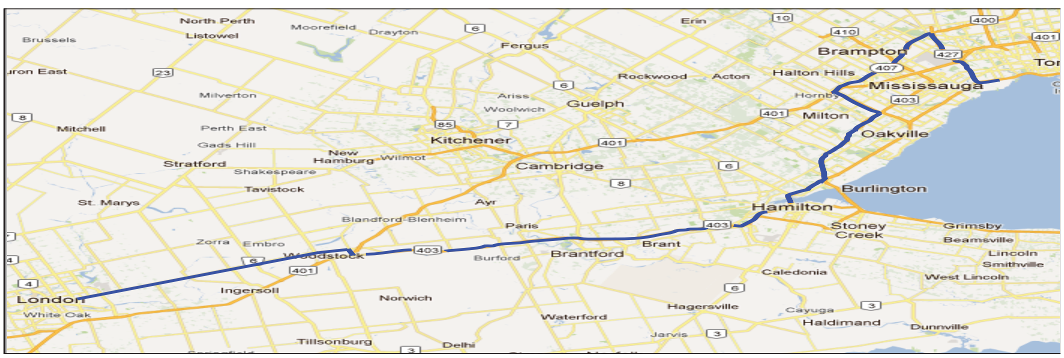
4.5.2 Performance Analysis for TSADA's Doctrines

One can observe in Figure 4.12 three routes of three travelers assuming identical start and destination addresses. In other words, the three travelers started at the same point in time, from the same initial address S to the destination address D. The prevalent traffic attributes A_r at the time are the same for all of them. However, each traveler has a different doctrine. Because their doctrines are different the optimum route for one each of them is different.

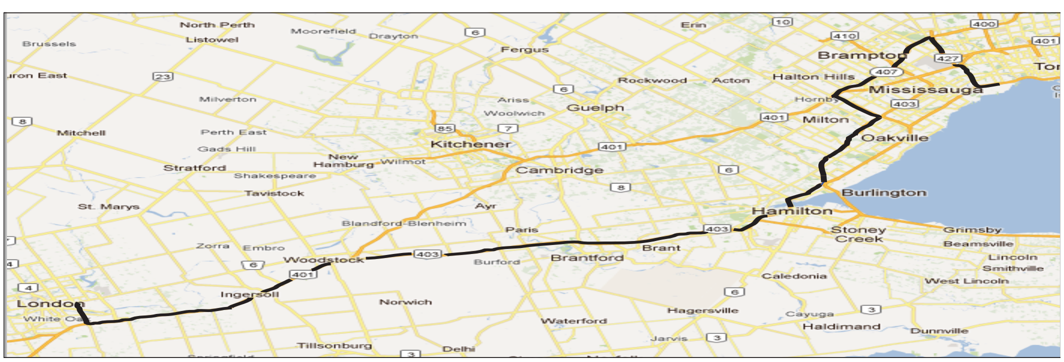
In the next Section, we show an experiment that is conducted in order to evaluate a road segment that has the following attributes: the average speed on the road is "high", the congestion is considered moderate, and the road segment is determined to be "Unsafe". Both safety and congestion is assessed using the model introduced in Section 4.3.2.



(a) Driver Using TSADA In The Speed Doctrine



(b) Driver Using TSADA In The Compound Doctrine



(c) Driver Using TSADA In The Safety Doctrine

Figure 4.12: Comparison of TSADA's *Speed*, *Safety* and *Compound* Doctrine.

4.5.2.1 Speed Doctrine Assessment

Figure 4.13 depicts a scenario where TSADA is using the *Speed* doctrine. One can see in this doctrine that the trip route emphasized road segments with high average speed and minimum traffic congestion. Under this doctrine the recommendation was recommended with extra cost. This result of the average speed doctrine is an example where safety has a minor effect on the final situation assessment.

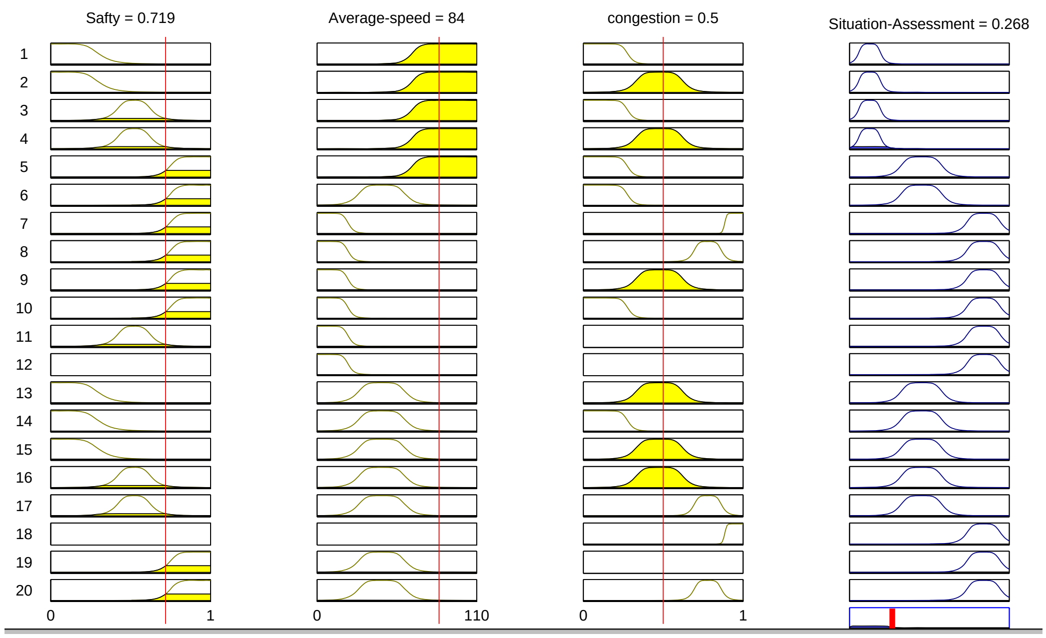


Figure 4.13: Inference System Based on the Average Speed Doctrine.

4.5.2.2 Safety Doctrine Assessment

The same road is assessed under the *safety* doctrine; however, the result is as expected and as depicted in Figure 4.14, different form the *speed* doctrine scenario. The result is expected because the road is determined to be “unsafe”, and it is subsequently deemed to be *not recommended*. The decision rule, rule 17, is shown in Figure 4.14, which clearly shows that since the safety level falls in the fuzzy set "unsafe", the final assessment is that the route is "*not recommended.*"

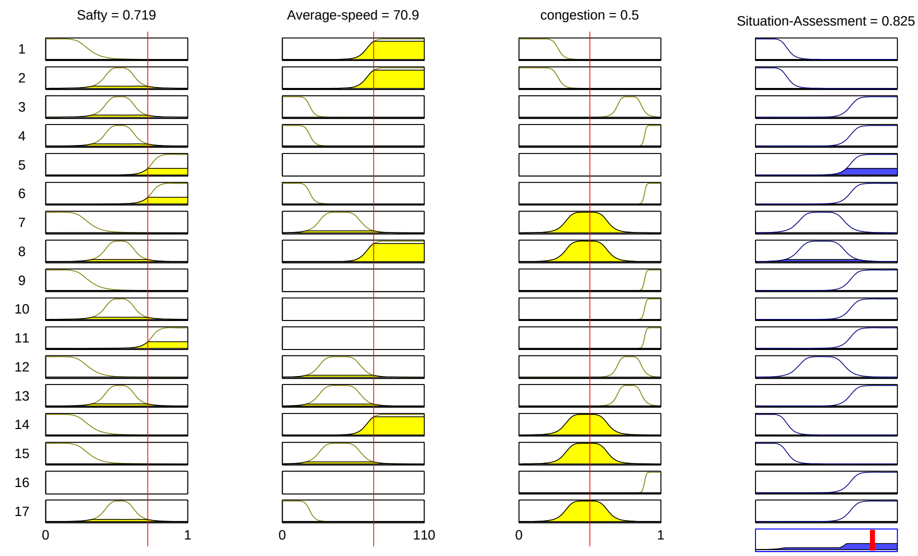


Figure 4.14: Inference System Based on Safety Doctrine.

4.5.2.3 Compound Doctrine Assessment

In the *compound* doctrine, the set of rules are used to reason both criteria of safety and speed in order to determine the best possible route. In this example, the road is unsafe but yet fast. In terms of fuzzy sets, the result belongs to the *recommended-with-cost* set, (Figure 4.11). However, the crisp value, which is later used to devise a route decision, is closer to the crisp value in the *safety* doctrine scenario, than that in the *speed* doctrine. In other words, the *compound* doctrine assessment in this case is similar to the assessment made by TSADA's *safety* doctrine. This similarity can be explained by an examining the congestion factor. In this example, the congestion was moderate, which added some concern about safety, which led to this similarity.

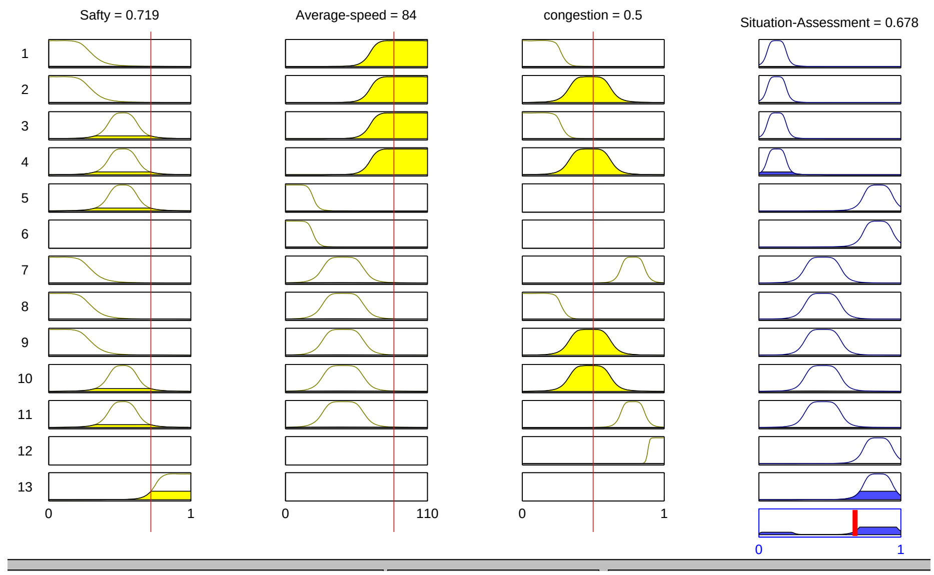


Figure 4.15: Inference System Based on the Compound Doctrine.

4.6 Summary

In this chapter, the situation assessment module is described in detail. The chapter introduces a hierarchical fuzzy approach used for situation assessment is explained in detail, with supporting figures showing its different levels and components.

The concept of doctrines is presented, and the three doctrines that deal with safety, average speed and the combination of both (i.e., the *compound* doctrine) is described. An example of rule-based inference engine is introduced, along with a discussion on how it handles traveler doctrine. Finally, a scenario whereby the proposed system demonstrated proper response to variations in the traveler doctrines is presented.

Chapter 5

Decision-Making for Trip Planning

5.1 Introduction

This chapter discusses the functionalities of TSADA's decision-aid module. It presents the underlying mathematical formulation for the route selection process. This mathematical formulation includes the definition of the trip planning objective function and decision constraints. Time and money constraints are chosen for consideration; many possible constraints can be considered in a similar manner.

This chapter presents a proof of concept of TSADA. Experimental work to evaluate different aspects of TSADA is also reported. In this experimental work, several scenarios are considered. A commercial personal navigation system (GNSS) is used to perform a comparative analysis under various doctrines and constraints.

5.2 Decision Making in TSADA

The final decision about the optimum route is approached as a decision making process. The optimum path is the one that takes the traveler from his/her initial location to the target destination and at the same time satisfying the traveler's route preferences. These preferences capture aspects such as safety, comfort, country roads, highways, etc. In computing the optimum route two factors are considered. The first is the cash allowance for the trip, which would include cash to be spent on gas, toll roads, insurance, etc. The other factor is the traveler's time allowance. Both allowances reflect the traveler's flexibility with respect to the monetary cost and time of the trip. TSADA takes advantage of these factors to explore routing options that are optimum in a broad sense to the extent that they go beyond shortest distance and shortest time in defining optimality. Due to the influence of other preferences, the optimum route might not prove to be the one with the shortest trip time or shortest distance possible.

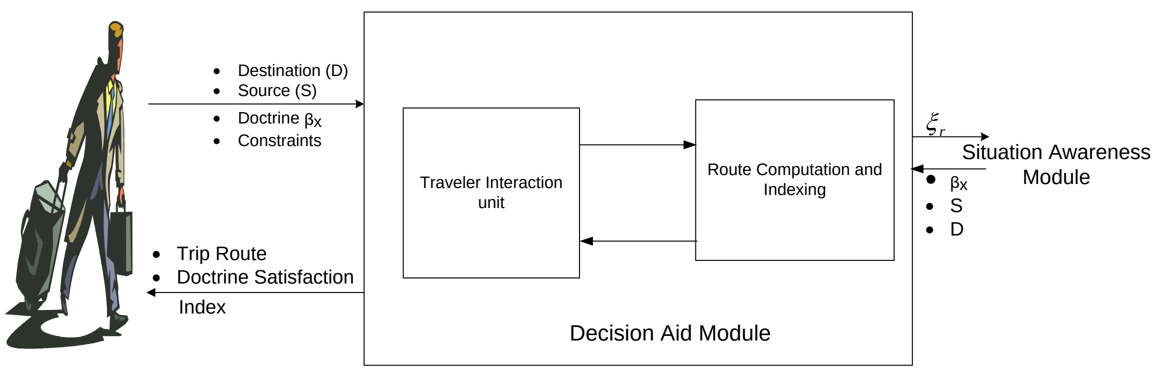
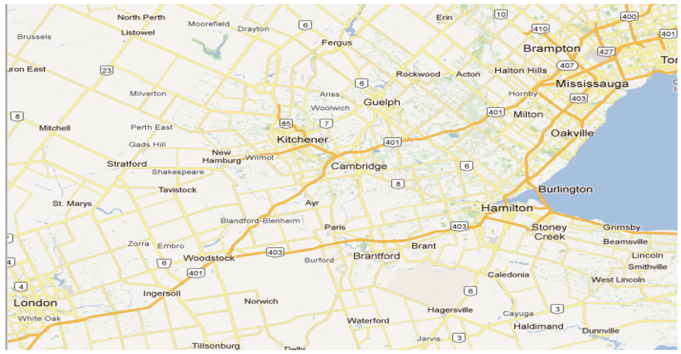
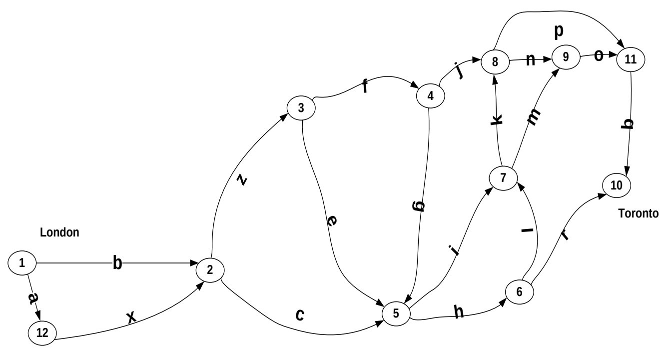


Figure 5.1: Decision aid module.

The decision module in TSADA system has two types of input: 1) Traveler's trip constraints (i.e., trip-time and trip-budget). 2) Cost of each road segment l_i. This cost is computed in the situation assessment module based on the traveler's preferences. The decision is to find the optimum route r that minimizes the cost $\xi_r^{tm_i}$, subject to the traveler's demands of trip-time τ_r and trip-budget ψ. The trip is formulated as a graph based combinatorial problem, in which the decision aid module is responsible for finding the feasible routes $R(S, D)$ based on the initial location S and the final destination D. The initial location changes every time there is an inquiry about the



(a) Road network map covers the area of interest taken from Google Maps.



(b) A schematic graph corresponding to the road network of interest.

Figure 5.2: Mapping a satellite map to graph based on the area of interest.

optimum route during the trip as the vehicle travels. Road segments, L_r, are also specified by the decision aid module. Each $l_i \in L_r$ has a cost, ξ_i, attributed to it computed by the situation awareness module.

The problem of finding the best route can now be stated as follows: Given a graph $G = (V, E)$, where V is the set of all nodes (vertices) in the graph, E denotes all edges in the graph. The graph represents an area of interest $R(S, D)$ that includes the starting point S and the destination point D of the trip. This area of interest is defined prior to the trip planning to limit the search space $R(S, D)$ (Figure 5.2). The goal is to find the best route, r_{Opt} with minimum cost ξ_r. The work in this thesis assumes one travel means, tm_i, and that is using a vehicle by which the traveler commutes from one point to another. The trip-planning problem with preferences windows is formulated as the follows:

$$\min \sum_{\forall i,j \in E} \xi_{r_{ij}}\, x_{ij} \tag{5.1}$$

Subject to:

$$\sum_j x_{ij} - \sum_j x_{ji} = \begin{cases} 1 & \text{if } i \text{ is a starting node} \\ -1 & \text{if } i \text{ is a destination node} \\ 0 & \text{otherwise} \end{cases}, \forall i \tag{5.2}$$

$$\sum_{j,j \in A} t_{ij}\, x_{ij} \leqslant \tau^k \tag{5.3}$$

$$\sum_{j,j \in A} m_{ij}\, x_{ij} \leqslant \psi^k \tag{5.4}$$

$$x_{ij} \in \{0,1\} \tag{5.5}$$

where

ξ_r = Recommendation value,

E = Set of nodes in the net,

τ = Time window,

ψ = Monetary budget window,

t_{ij} = Travel time over the segment ij ,

m_{ij} = Cost of travel over the segment ij ,

k = Trip query index,

x_{ij} is the decision variable representing the road segments and is defined as

$$x_{ij} = \begin{cases} 1 & \text{if the road segment is selected} \\ 0 & \text{otherwise} \end{cases} \tag{5.6}$$

The Constraint in Equation 5.2 stipulates that the driver leaves the starting point and eventually arrives at the end point and never uses the same road segment twice. The inequality in Equation 5.3 states that the trip time is never more than τ indicated at the query time k. The inequality in Equation 5.4 ensures that the total cost of the road segment does not exceed ψ at query time k. The last, constraint, Equation 5.5, is the integrity constraint.

5.2.1 Doctrine Satisfaction Index

The decision aid module provides the traveler with the optimum route r_{Opt}, and with doctrine satisfaction index. This index represents the goodness of the chosen route in light of the traveler doctrine and constraints. The *speed* doctrine has doctrine satisfaction index of the actual average speed throughout the trip. The traveler receives a map with the optimum route and some statistical information about the max, min and average speed throughout the trip. The information will provide the traveler with an idea of how much his/her doctrine influenced the trip planning process.

For a traveler X, the minimum trip cost ξ_r for the optimal route r is used to compute the doctrine satisfaction crisp, D_{S_c}. For each road segment l_i, $l_i \in L_r$, there is ξ_i, where $\xi_i \in \xi_r$. Furthermore, $\forall\ l_i \in L_r$ there is a known distance length $\hat{l}_i$. D_{S_c} is defined as follows:

$$\hat{L_r} = \sum_{\forall i \in r} \hat{l_i} \tag{5.7}$$

$$D_{S_c} = \sum_{\forall i \in r} \frac{\xi_i * \hat{l_i}}{\hat{L_r}}. \tag{5.8}$$

Four levels of satisfaction are defined:

$$D_{S_r} \in \{\textit{Highly satisfied}, \textit{Satisfied}, \textit{Marginally satisfied}, \textit{Unsatisfied}\}. \tag{5.9}$$

An example of how the doctrine satisfaction index D_{S_r} is computed is depicted in

Figure 5.3. For instance, D_{S_c} computed to be 0.2 thus D_{S_r} is *Highly satisfied*. These satisfaction levels are mapped to the three membership functions of the road recommendation model as depicted in Figure 5.3.

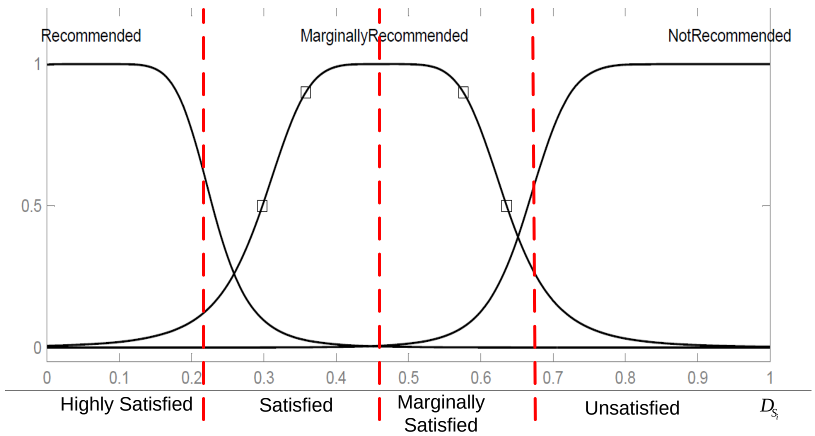


Figure 5.3: Doctrine satisfaction index computation process.

5.2.2 Safety Risk Exposure Index

In the *safety* doctrine, a trip safety risk exposure index is provided. Travelers using this doctrine are provided with figures and numbers that show them how much safety risk they are, or will, be exposed to during their trip. It is intuitive that the chances of being at high risk become greater after repetitive exposure to a low-risk activity. The following scenario illustrates this point: a driver may use roads that have statistically low accident rates. There are also other roads that have a low incidence of the absence of cellular coverage. If in addition, some of these roads have a small amount of snow,the traveler may end up being exposed to some degree of cumulative risk. If the principle of the *safety* doctrine is in effect, the issue of determining how much safety the traveler has been allocated during his/her trip, or, conversely, how much risk the traveler has been exposed to during trip. In this research, low risk is perceived as safety gained.

5.3 Experimental Work

TSADA, as explained in Chapter 3, is comprised of three layers. For our scenarios, the following assumptions are made:

1. The area of interest covers a transportation network, which covers a wide area and includes roads that have different topographies and weather conditions.
2. Traffic attributes, A_r, are represented by the middleware layer at the time of the request in real time.
3. The sensor networks covers the designated area.
4. Communication between the drivers and TSADA is established and maintained at all times, or at least at the time the request is made and the answer is received.

To prove the efficiency of TSADA, an experiment is conducted in which multiple scenarios are analyzed as four types of navigation systems are used in the simulated scenarios. All drivers have the same starting and destination points and starting times. One type is a traditional commercial navigation device. The other three types employ the proposed system, but each represent one synthesize one specific doctrine, namely: *speed, safety and compound.*

5.3.1 Experimental Implementation and Results

The developed TSADA system is tested for all three doctrines and is compared in performance with the commercial navigation device. Four travelers were used in the simulation, Figure 5.2(b). Examples of attributes of the simulated roads are shown in Table 5.1, according to the map shown in Figure 5.2(b). In the following subsections, the doctrine effect on the trip planning and on the doctrine satisfaction D_{S_r} is investigated. The three scenarios are provided along with the results. Different preferences and constraints are tested in these scenarios.

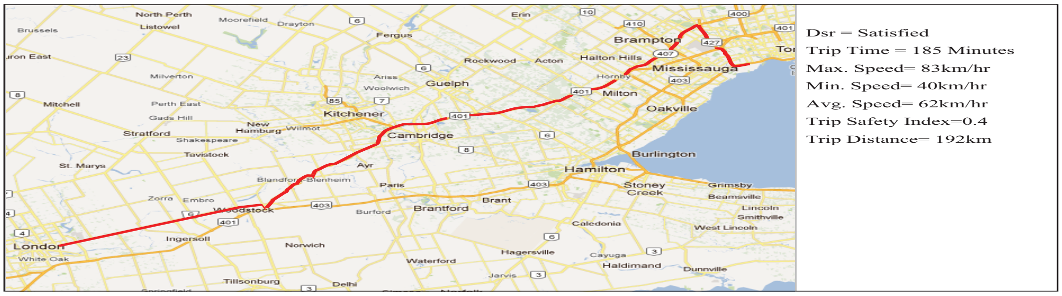
Table 5.1: Simulated traffic attributes A_r.

x_{ij}	length(km)	S_{limit} (km/hr)	Width (m)	Price	Snow	Black Ice	Occupancy	$S_{average}$ (km/hr)
a	8.1	60	6	0	low	No	med to high	slow
x	45.3	100	9	0	low	No	med to low	fast
b	50.7	80	6	0	low	No	low	fast
c	64	100	9	0	low	No	med to high	medium
z	43	100	9	0	high	No	med to low	fast
e	47.5	80	3	0	medium	Yes	low	fast
f	22	100	9	0	low	No	med to low	fast
g	25.7	90	3	0	medium	No	med to low	fast
h	29.6	100	9	0	low	No	high	medium
i	30.3	100	9	0	low	No	low	fast
j	30	100	9	0	low	No	med to low	fast
k	9.3	100	9	0	low	No	low	fast
l	4.9	100	9	0	low	No	med to low	fast
m	15.5	100	9	0	low	No	med to high	slow
n	13.1	100	12	0	low	No	high	slow
o	7.5	100	12	0	low	No	high	slow
p	24.2	100	9	12	low	No	low	fast
q	22.6	100	9	0	low	No	high	slow
r	31.6	100	9	0	low	No	high	slow

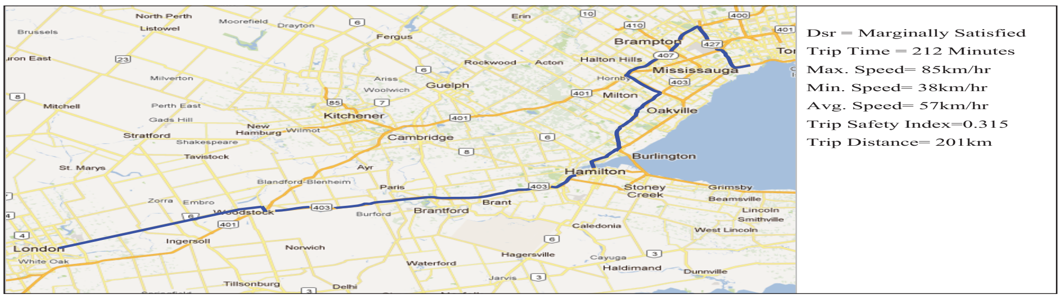
5.3.1.1 Doctrine Effect on Trip Planning and Doctrine Satisfaction Index

To test the optimality of the routes computed by TSADA with respect to the travelers's doctrine, we simulate four travelers, three of which are using TSADA's doctrines: *Safety*, *Speed* and *Compound* doctrine. The fourth driver is using a GNSS with preference of fastest route. The computed trip plans are depicted in Figure 5.4 and showed in Table 5.2.

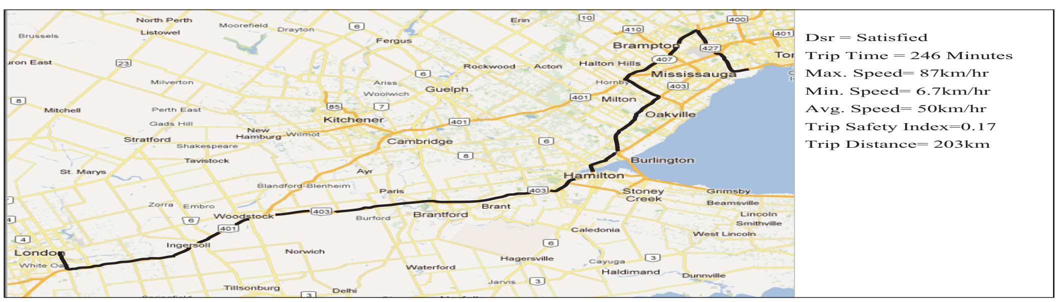
It can be seen that TSADA provides the traveler with the route that is influenced with his/her doctrine as much as possible. In this particular scenario, non of the



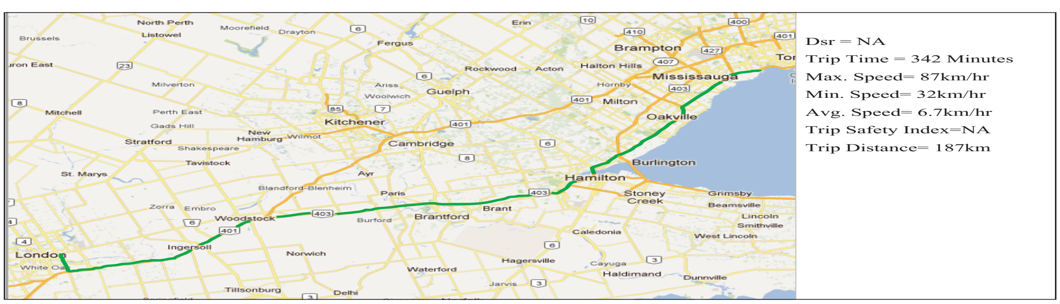
(a) Driver using TSADA in the speed doctrine



(b) Driver using TSADA in the compound doctrine



(c) Driver using TSADA in the safety doctrine



(d) Driver using GNSS

Figure 5.4: Comparison between TSADA's doctrines and commercial GNSS.

Table 5.2: Optimum routing using TSADA and GNSS.

Trip planner	Doctrine/mode	D_{S_r}
TSADA	*Speed*	*Satisfied*
TSADA	*Compound*	*Marginally satisfied*
TSADA	*Safety*	*Satisfied*
GNSS	Fastest route	NA

travelers is presented a route that has a *Highly satisfied* D_{S_r}; optimal routes for TSADA are routes that can meet as much as possible of the traveler's doctrines and constraints (i.e., demands and presences). However, we can see the all travelers were able to achieve an acceptable level of satisfaction, and at all time a higher performance than the traveler who is using the GNSS.

In the next scenarios, we investigate TSADA's performance compared to the commercial navigation device, as well as the effect that each doctrine can make on the decision of the optimal route.

5.3.1.2 Scenario 1: Comparing TSADA Different Doctrines and GNSS with Open Resources

In the first scenario, the four travelers are dispatched into the simulation environment shown in Figure 5.2(b). All travelers have unlimited resources with respect to the trip budget allowance and time. The traveler using the commercial navigation device chooses the shortest route as the basis for the decision about the optimum route. The other three travelers are each assigned a unique TSADA system doctrine. All four travelers want to arrive at the same destination D with their preferences being satisfied as follows: the shortest-route traveler prefers the shortest possible route. The speedy-route traveler prefers the route with the highest average speed compared to all other feasible routes. The safety -route traveler prefers the safest route, while the traveler using the compound doctrine prefers the safest route with the highest possible average speed. Naturally, all four travelers also want to arrive to their destination as quickly as possible. The shortest route is a fixed route at all times, since the length of the road does not change. However, the trip time varies from one trip to another. Hence, in this scenario, the criterion based on which a plan can be viewed as successful plan is the comparative trip time for the choices of both the shortest path and the fastest path.

Scenario 1: Results and discussion

Figure 5.5 shows the results of the trip in terms of total trip time versus progress expressed as distance traversed. With respect to goal satisfaction, all four travelers satisfied their initial preferences. The traveler using the GNSS took the shortest path, while the preference of the other travelers were met with respect to speed and safety risk exposure. However, although the initial preferences were satisfied, another important factor in any trip should be examined: the trip time.

All the travelers who used the TSADA system arrived earlier than the traveler who is using the GNSS. Figure 5.6 shows that the traveler using GNSS in the fastest route mode arrived after the traveler that used the TSADA system in speed doctrine by a time lag of 100 minutes for almost the same distance. This result proves the effectiveness of the TSADA system if trip time is involved in the evaluation process because the TSADA system uses online information so that it is aware of the surrounding environment. Rather than searching for the fastest route based on the maximum speed permitted, the TSADA system searches for the fastest route based on the actual speed at the time of the inquiry.

The experiments in this scenario were under no constraints in terms of money or time. The results would differ regarding the preferred route for the same doctrine if the trip planning was constrained by money or by total trip time. The next scenario revealed how the TSADA system whilst in speed doctrine reacts under budget constraints.

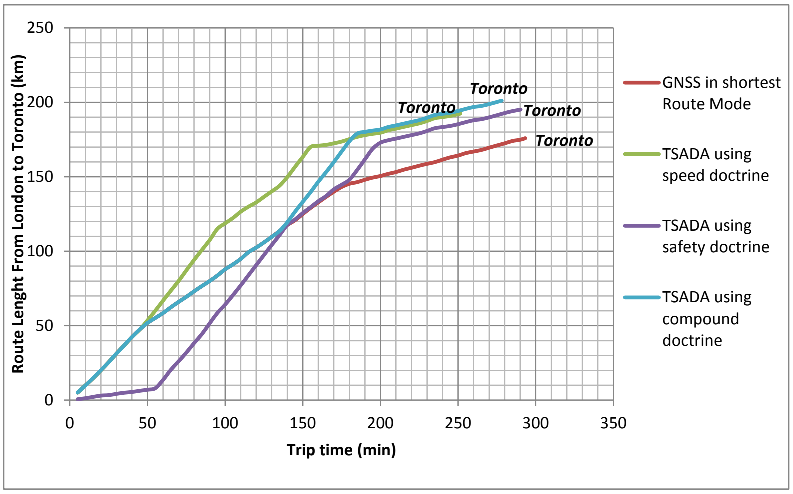


Figure 5.5: Path-planning for preference-based trip.

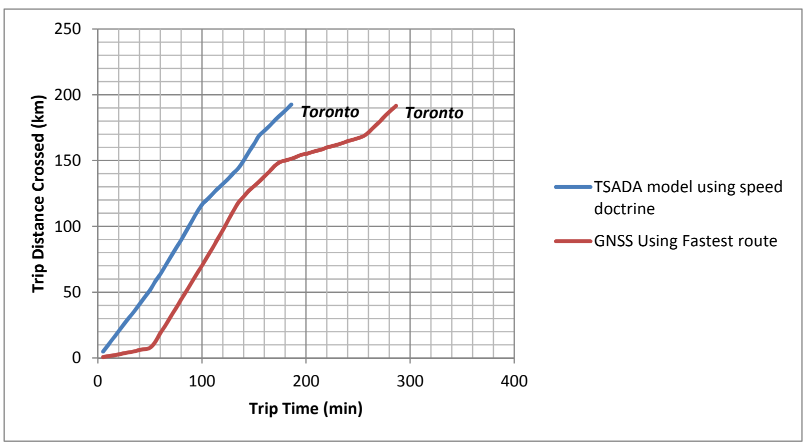


Figure 5.6: Comparison of one traveler using the TSADA system and one using commercial navigator in the fastest route mode.

5.3.1.3 Scenario 2: Comparing the TSADA System in Speed Modes and Commercial GNSS for Different Budget Window Preferences

In this scenario, three travelers were simulated, all using the speed doctrine of the TSADA system. Each traveler had its own set of cash constraints. First, The traveler using with commercial GNSS was simulated and compared to the speed doctrine of the TSADA system under the same budget constraint.

In the simulated environment, certain road segments were, as indicated in Table 5.1, assigned a price tag; when a traveler crosses these road segment, he/she pays a price for the use of that segment. Other road segments were free of charge, so no money is paid when a vehicle is traversing them.

This experiment is conducted in order to show that the results of the TSADA system can be differ, given the same amount of information and using the same doctrine but with different money constraints. The speed doctrine means that the travelers prefers roads with high average speed; however, if cash is constrained, it is expected that the decision about the optimal route would be different every time this constraint is adjusted.

The second part of this experiment is concerned with comparing the commercial GNSS with the TSADA system using speed doctrine when there is no cash allowance. The goal is to demonstrate that under the same conditions, although it is tightly constrained, the TSADA system in speed doctrine provides a shorter trip time than that obtained from the commercial GNSS.

Scenario 2: Results and discussion

The individual performance of TSADA system in speed doctrine differs from traveler to another based on the allowed budget for the trip.

As expected, when the cash allowance is relatively high, the TSADA system has a higher degree of freedom in choosing the best possible route. However, when the cash allowance is smaller, the system is forced to choose a route that is almost free of charge, as shown in Figure 5.7. The time difference between the traveler that is allowed to use 25 cash unit and the traveler that is allowed to use 2 cash units is about 115 minutes.

Figure 5.8 presents a comparison of two travelers under tight financial constraints. One traveler used the commercial GNSS and the other traveler is using the TSADA system in speed doctrine. The results shown in Figure 5.8 prove that even if the TSADA system in speed doctrine was limited to only-toll free routes the TSADA system still performed better than commercial GNSS, providing a route that resulted in an arrival time that was almost 30 minutes earlier. This efficiency can be attributed to the online information fed to the TSADA system because systems receiving online information are bound to provide better decision than systems that operate based on stored or offline information.

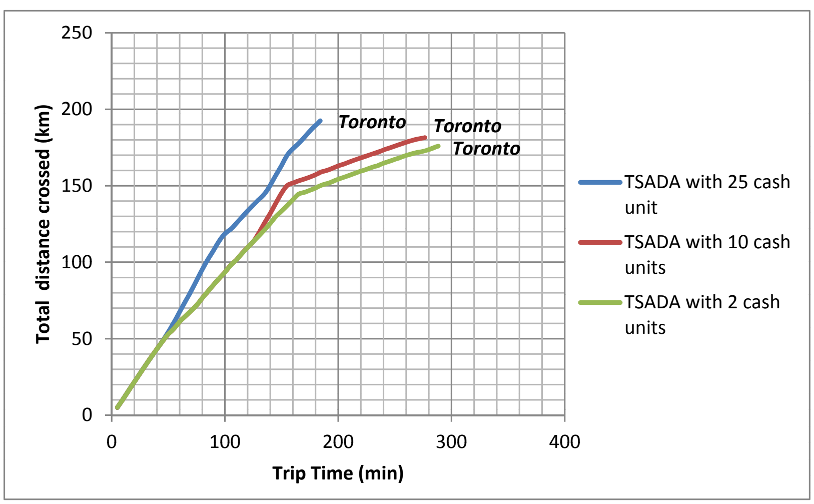


Figure 5.7: Route decision for travelers using TSADA system in speed doctrine with different budget windows.

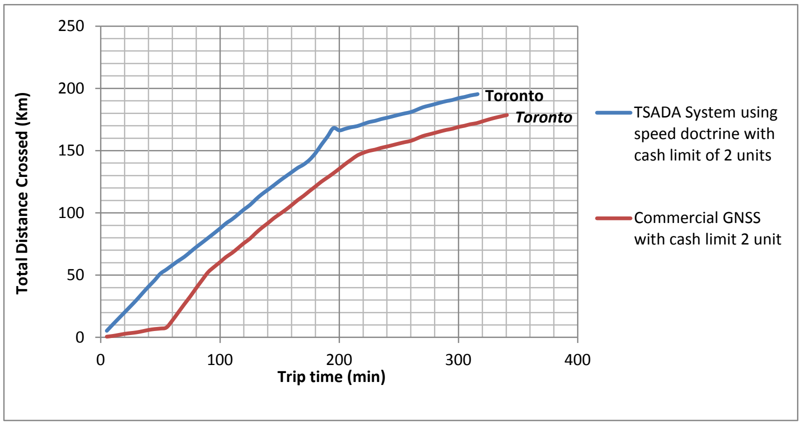


Figure 5.8: Comparison of two travelers one using the TSADA system and one using commercial GNSS in fastest route mode with cash limit of 2 units.

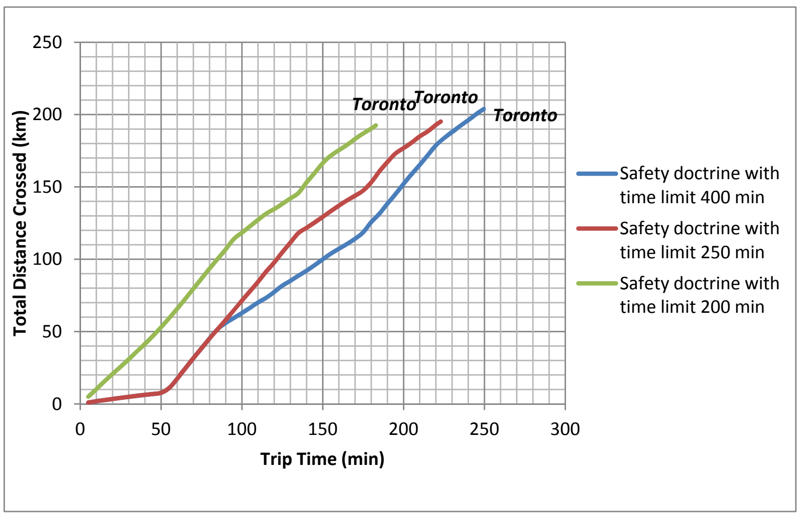


Figure 5.9: Comparison of route decisions for the TSADA system in safety doctrine for different time preferences Windows.

5.3.1.4 Scenario 3: Comparing the TSADA system in Safety Doctrine for Different Time Window Preferences

The third scenario simulated three travelers that were using TSADA system using the safety doctrine. The main goal of this experiment was to reach the trip destination D while adhering to the safety doctrine. However, each traveler was given a different trip time limit in order to investigate the effect of the trip time window on the decision produced by the TSADA system using the safety doctrine. It is expected that the decision about the best route would change based on the time window imposed. However, a change in the suggested route might also imposes the possibility of an

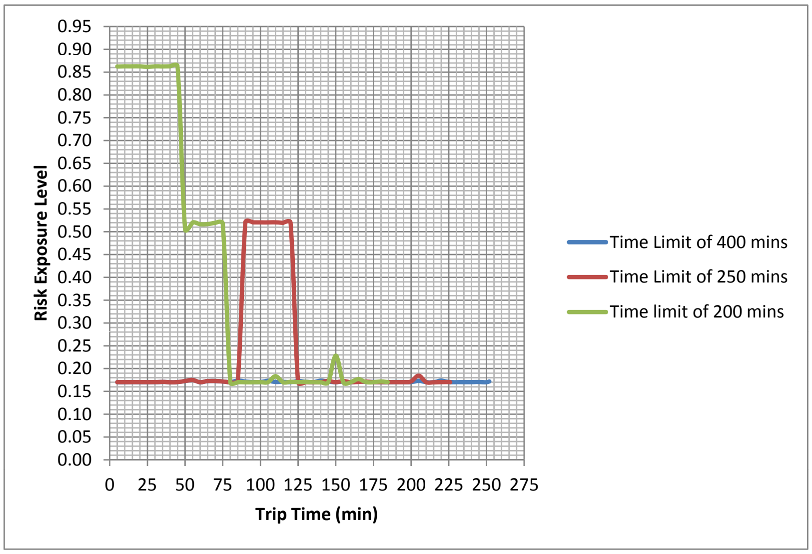


Figure 5.10: The effect of changing the time window on the risk exposure in safety doctrine based trip.

exposure to some level of safety risk. The amount of this safety risk for each traveler was also investigated.

The goal of this experiment is to show that the safety risk exposure that results when the system operates in safety doctrine is much less that the risk exposure in the speed doctrine. The travelers used for this scenario were given a time limit restricted to 250 minutes, which is a little bit longer than the trip time that could be obtained in the speed mode.

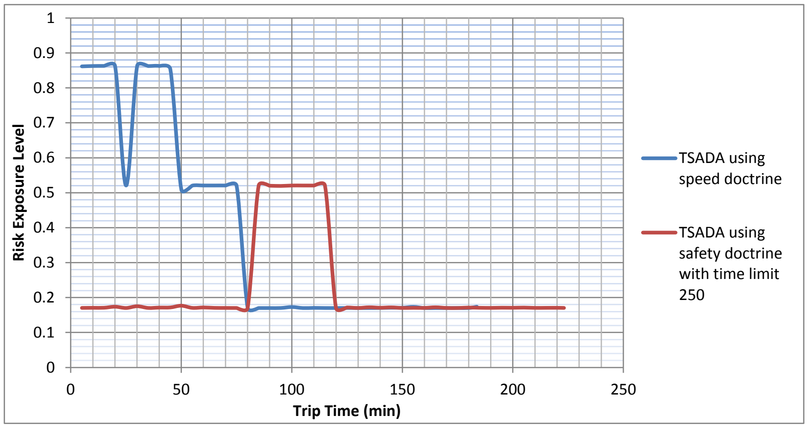


Figure 5.11: Comparison of risk exposure in the safety mode and speed mode.

Scenario 3: Results and discussion

The main constraint that can limit the results produced by the TSADA system using the safety doctrine is the desired trip time. As show in Figure 5.9, the travelers using the TSADA system in safety doctrine complied with the time constraints. However, as shown in Figure 5.10, the level of safety risk exposure changes as the time constraints change and it can be seen that when an open time constraint is permitted, the safety risk exposure factor remains stable at a low safety risk level during the entire trip. This result shows that, while in the safety doctrine, the TSADA system works well to keep safety risk exposure as low as possible. Figure 5.10 shows the level of risk exposure for three travelers that were allotted varying trip times.

As shown in Figure 5.10, the first traveler with a time limit of 400 minutes, which is considered an open time window, has sustained a constant low level of safety risk exposure at all times during the trip. However, the other two travelers that were not given an open time and had different plans for their trip based on the their desired time window. The traveler with a time limit of 250 minutes was exposed to constant low risk for about 40 minutes, while the traveler with a time limit of 200 minutes was exposed to high safety risk for 80 minutes and then low risk for another 10 minutes.

The trip times for the three travelers are shown in Figure 5.9. However, a comparison of the TSADA system in speed doctrine and the TSADA system in safety doctrine with a time window of 250 min revealed that even when constrained by time, the TSADA system in safety doctrine produced results with less safety risk exposure than it did in speed doctrine, as shown in Figure 5.11. This result proves that the doctrines incorporated into the TSADA system have a direct and strong influence on the overall decision about the best route, regardless of the window constraints input by the traveler.

5.4 Discussion

Figure 5.2(b) shows the roads and possible routes in an area of interest between a specific initial point S and a specific destination D. The simulated environment incorporated a variety of attributes A_r that involved traveler preference to be considered during the decision-making process. The comparison initially involved both a commercial GNSS and the TSADA system developed according to the system presented in this work. Due to its awareness of the environment in which the trip will take place, TSADA produced a more effective response than the commercial GNSS. In addition, the introduction of the doctrine concept evaluates the TSADA system to operate in its different doctrines. The safety, average speed and compound doctrines have been constrained by the specific preferences by the user of the system: budget and cash allowances; and preferred trip time. Based on the variations in these preferences, each doctrine produces various possible routes, each of which can be labeled as an optimum route. The decision made by the TSADA system is considered successful if it satisfies the preferences demanded by the traveler, this satisfaction is indicated by the doctrine satisfaction index. The trip advice provided by the safety doctrine is considered effective when the safety risk exposure is minimal, and safety risk exposure is calculated for each instant throughout the course of the trip. On the other hand, the average speed doctrine is evaluated on the basis of trip time because the average speed doctrine can be thought of as a mean of achieving minimum trip time. The compound doctrine is evaluated based on a combination of the risk exposure throughout the trip and the trip time.

Central to the implementation of the doctrines is the use of a hierarchical fuzzy inference engine. The assessment of the situation at level two and three is performed only once. Using the outcome of these sub-situation assessments, it is possible to implement a situation assessment for the road recommendation level as many times as the requested based on the doctrines. At this stage, most of the calculations have already been performed, and the results are ready to be used in any manner required.

5.5 Summary

This chapter has presented the structure of the decision-aid module of TSADA, including the mathematical formulation based on which the final decision about the best route is produced.

The mathematical formulation incorporates an objective function for capturing the routes costs. An optimization formulation uses this function to determine minimum cost routes, subject to traveler preferences and route constrains. Time and money are determined to be the main trip limitation windows according to which the decision about the best route may change.

Experimental work is conducted under different scenarios to illustrate the capabilities of the TSADA system. The performance of the TSADA system under various doctrines is investigated and compared against that of GNSS. The performance of the doctrines is also tested for a variety of constraints with respect to traveler preferences. Safety risk exposure analysis for the different mode of the TSADA model is also investigated in order to prove the effectiveness of the safety mode in the TSADA model.

Chapter 6

Conclusion and Future Research

The research presented in this thesis has resulted in the design of a trip-planning system, which has been implemented for traveler centric trip planning. This chapter summarizes the research and experimental work conducted in this research and provides suggestions for future work.

6.1 Conclusions

A traveler-centric trip planning system has been introduced. Each component of this system has been described, with the primary focus on trip situation assessment and the decision-aid unit. For the situation assessment module, a hierarchical fuzzy inference system has been incorporated.

The concept of doctrines is defined and incorporated into the trip planning system. Doctrines are categorized into three types: the average speed based doctrine, the safety of a trip based doctrine, and the compound doctrine that covers aspects of both safety and speed doctrines.

For the decision-aid module, trip planning is modeled as a graph model, with the objective of determining the route with the minimum cost subject to monetary and time constraints. The mathematical formulation for the trip-planning problem has been presented.

Experiments are conducted in order to demonstrate the effectiveness of the TSADA system and to compare it with a commercial navigation (GNSS). The experimental results show the various decisions produced by TSADA depending on doctrine used. TSADA's effectiveness is investigated and compared with a commercial GNSS. Also, TSADA trip plans have shown satisfactory results based on the doctrine satisfaction index that has been devised to linguistically describe the expected traveler satisfaction after.

6.2 Future Work

In this section, some of the important issues related to TSADA that can be addressed in future work are discussed.

6.2.1 Future Directions for TSADA

TSADA includes a number of units, each of which can be considered as an area of research for future work:

1. The situation assessment module used in this research uses a hierarchical fuzzy inference engine; other tools can be considered. The number of levels in which situation assessment is conducted can be adjusted, with the goal of obtaining a better assessment.

2. A number of factors are associated with the safety doctrine. For simplicity, only weather conditions and traffic conditions have been considered as measures to

compute road safety index. Other factors, such as cellular coverage and quick access to hospitals and rescue teams can be considered as well.

3. Prediction techniques are important for determining traffic conditions in the future (e.g., average traffic speed and the weather forecast); and can be employed in order to provide better planning for future trips.

4. The decision to events association unit can be presented in many forms, which should be investigated.

5. Different transportation means can be accommodated in TSADA.

A few additional factors can be considered in the determination of the best route. When the road recommendation level is computed, possible factors that can be investigated are:

1. The amount of gas available, the routes that have gas stations nearby, and how far the vehicle must travel to reach its destination.

2. The existence of residences available for traveler to use for temporary accommodation as well as the prices associated with these residences can be used as an option for limiting the selection of possible routes.

3. The availability of parking areas needed during the trip can be factored into the determination of the best route as well.

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