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A Review of Travel Time Reliability Models in Transportation Networks under Uncertainty

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ABSTRACT
Travel Time Reliability (TTR) is a key indicator for measuring the efficiency and service quality of transportation networks, which has a significant impact on stakeholders such as travelers, service providers, planners, and managers. With the growth of transportation demand and the increasing complexity of the system, traffic congestion and travel time uncertainty have become more prominent. Therefore, researching TTR is of great practical significance. This paper reviews the relevant research on travel time reliability models in transportation networks, covering the concept of TTR, measurement methods, influencing factors, and the application of multi-objective optimization methods in TTR research.

KEYWORDS
travel time reliability; transportation networks; traffic assignment; multi-objective optimization

1 Introduction

Travel Time Reliability (TTR) is vital for evaluating transportation networks. It significantly impacts travelers, service providers, planners, and managers. Empirical studies show travelers often weigh TTR as much as or more than travel time (Hollander, 2006; Li et al., 2010). For instance, they consider both average travel time and its uncertainty when planning trips. Planners and project evaluators must factor in TTR cost, as overlooking it can lead to infrastructure projects failing to meet needs (de Jong and Bliemer, 2015). Service providers and traffic managers use TTR to monitor and enhance service quality (Lyman and Bertini, 2008; Kim, 2014). With growing transportation demand and system complexity, congestion and travel time uncertainty are worsening, especially during urban peak hours. Researching TTR thus holds great practical value. For transportation planning, understanding TTR helps develop better plans and strategies, like optimizing facility layout. For travelers, TTR assessment aids trip planning, and in business, it's key for logistics efficiency.

This paper comprehensively reviews TTR models in transportation networks. It delves into TTR concept, measurement, influencing factors, and multi-objective optimization applications. By systematically reviewing literature, it analyzes existing research pros and cons, guiding future studies. The scope covers TTR modeling, evaluation, value quantification, and traffic assignment, with an emphasis on multi-objective methods, which better reflect travelers' preferences and real-world traffic for more scientific planning and decision-making.

2 Travel Time Reliability Models

2.1 Concept and Measurement of TTR

TTR, defined by travel time uncertainty, measures trip completion reliability within a set period. Existing research uses various indicators. Probability-based ones define TTR as the probability of on-time arrival (Chen et al., 2017). Higher probabilities mean better TTR, directly showing travel time uncertainty's impact. Moment-based indicators like variance measure travel time distribution dispersion (Carrion and Levinson, 2012). Larger values indicate lower TTR and less stable travel times. Percentile indicators, such as 90th/95th percentile travel time, consider extreme scenarios, crucial for punctuality-focused travelers and managers. Mathematical programming methods balance travel efficiency and cost using concepts like effective travel time and travel time budget (Senna, 1994; Lo et al., 2006), mirroring real-world travel decisions. Each measurement indicator has its own advantages and disadvantages. Probability-based ones are intuitive but don't fully capture travel time distribution. Moment-based indicators quantify fluctuations but are insensitive to extremes. Percentile indicators focus on extremes, potentially overlooking middle-range data. Mathematical programming methods consider behavior, yet parameter determination is complex. In practice, choose an indicator based on specific needs and research goals.

2.2 Modeling Methods of TTR

2.2.1 Characterization of Travel Time Distribution (TTD)

The characterization of TTD is fundamental to TTR modeling. Existing research mainly employs two methods: fitting and derivation. The fitting method uses assumed distribution functions for travel time datasets (Zang et al., 2022). Common single-distribution models like the normal, log-normal, Weibull, and Gamma distributions (Lo and Tung, 2003; Watling, 2006; Siu and Lo, 2014) fit TTD with typical right-skewed, long/fat-tailed features. For example, the log-normal distribution suits urban road travel time data fitting. Mixture distribution models, via weighted combinations of single-distribution models, handle multimodal TTD from traffic disruptions or congestion (Chen et al., 2017), like near intersections. The moment-based modeling method directly uses travel time statistical info to fit TTD, avoiding distribution assumptions (HOU and TAN, 2009), but has high computational complexity. The derivation method gets the TTD model from TTR uncertainty sources (Zang et al., 2022), considering demand-side, supply-side, or both factors. Usually, it first determines the link TTD model and then aggregates to get route or network TTD models, using methods like the central limit theorem. Yet, these methods struggle with link TTD correlation and computational efficiency.

2.2.2 Value Quantification of TTR

The value quantification of TTR aims to measure the monetary value that travelers are willing to pay to improve TTR. Existing research mainly quantifies it through theoretical models, such as the mean-variance model (Jackson and Jucker, 1982), the schedule delay model (Small and Kenneth, 1982), the mean-lateness model (ATOC, 2005), and the network utility maximization model (Uchida and Kenetsu, 2014). These models are developed based on the concepts of travel time uncertainty models in empirical models. It can be seen from various studies that there are mainly two theoretical frameworks: the mean-variance model and the scheduling model. Jackson and Jucker proposed the mean-variance model , which incorporated the mean and variance of travel time into the utility function, initiating the study of travel time reliability from the perspective of risk. The mean-variance model considers that both the expected travel time and the variability of travel time are sources of negative utility:

$$U(T)=\eta_1\mu+\eta_2 Var[T]$$

In this model, travelers attempt to minimize the total negative utility brought by travel time and time variability. Although this model takes into account the expected travel time and travel time variability, it ignores travelers' scheduling cost. To fill this gap, Small (1982) expanded on the research of travel delays and incorporated scheduling cost into the model, forming the schedule delay model. Let *Arr* and *D* epresent the arrival time and departure time respectively. The basic formula of the scheduling delay model is:

$$U(D,T)=\eta_1 T+\eta_2(SDE)+\eta_3(SDL)+\eta_4 D$$

Where *SDE* represents the early travel delay; *SDL* represents the late travel delay; *D* is a binary variable, when $SDL>0$, $D=1$, otherwise, $D=0$. This model takes into account the negative utility of not arriving at the destination on time, further expanding the research dimension.

2.2.3 TTR-Based Traffic Assignment

TTR-based traffic assignment studies how TTR impacts individual travel behavior and network traffic flow. The core is setting route-selection criteria with TTR in mind. Research views travelers' TTR attitudes from objective quantification and subjective perception. For objective quantification, utility-based measures like expected utility (mean-variance, etc.) and non-expected utility (cumulative prospect theory, etc.) show travelers' risk attitudes. Risk measures using safety margins, such as travel time budget, help travelers in uncertain situations. Subjective perception accounts for travelers' perception errors in route selection, with assumptions of no, deterministic, and random perception errors (Zang et al., 2022). These assumptions affect traffic assignment model accuracy. TTR-based traffic assignment models are often variational inequality, nonlinear complementarity, fixed-point, or game-theory models (Shao et al., 2006; Ordonez and Stier-Moses, 2010; Mirchandani and Soroush, 1987; Bell et al., 2002). They face high computational complexity as route cost calculations in uncertainty involve uncertainty propagations and non-monotonic cost functions.

3 Application of Multi-Objective Methods in TTR Research

Multi-objective methods are crucial in TTR research, optimizing multiple TTR-related goals like minimizing travel time, maximizing TTR, and reducing costs. In network design, they determine the best network structure and capacity. For instance, Wang et al. (2014) developed a bi-objective user equilibrium model considering travel time and TTR, expanding the traditional single-objective model. In road pricing, multi-objective methods balance TTR and fairness. During peak hours, proper pricing can guide vehicle flow, ease congestion, enhance TTR, and ensure fairness. For traffic assignment, they consider travel time, TTR, etc., to optimize traffic flow distribution, improving network efficiency and reliability. Genetic, particle swarm, and simulated annealing algorithms are common multi-objective optimization tools. While they can find optimal/near-optimal solutions, large-scale transportation networks pose challenges in computational efficiency and convergence. In practice, choose an algorithm based on problem characteristics and adjust parameters according to the network situation for better results.

4 Conclusion

Research on travel time reliability (TTR) in transportation networks spans concept measurement, modeling, value quantification, and traffic assignment. Multi-objective methods are being increasingly applied. In TTR measurement, diverse indicators exist, yet their consistency and accuracy need refinement. TTD characterization methods have pros and cons, with room for improvement in link TTD correlation handling and computational efficiency. Uncertainty-based TTR models are more realistic but complex. TTR value quantification via different models lacks network-level research. TTR-based traffic assignment considers travelers' factors but has high computational complexity. Multi-objective methods have made progress in TTR research but require optimization in algorithm efficiency and practical use.

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