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学 位 論 文 内 容 の 要 旨

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Uncertainty-Aware Path Optimization and Multi-Scale Traffic Flow Modeling in Dynamic Transportation Networks

(動的交通ネットワークにおける不確実性考慮型経路最適化とマルチスケール交通流モデリング)

Uncertainty in transportation networks, arising from stochastic travel times, behavioral heterogeneity, and external environmental disturbances, has become a critical challenge for ensuring reliable network operation and efficient optimization. To address this issue, this dissertation establishes a comprehensive three-layer framework that integrates behavioral modeling, stochastic representation, and reliability-oriented optimization. The framework connects individual-level decision mechanisms with system-level optimization logic, providing a unified theoretical and methodological foundation for uncertainty-aware transportation system modeling.

At the behavioral level, a multi-class risk-sensitive path choice model (BST model) is developed to capture travelers' heterogeneous responses under non-extreme flood disturbances. The model introduces a risk-aversion coefficient to describe the degree of user sensitivity to uncertainty and constructs a composite stochastic utility function consisting of three components: perceived travel time, perceived flood risk, and path selection inertia. The first two components represent objective costs, while the third captures subjective psychological tendencies. Two independent stochastic terms, following Gumbel and uniform distributions, are introduced to represent cognitive uncertainty and behavioral asymmetry, allowing the derivation of a closed-form path choice probability. The model further defines dynamically adjusted sets of “acceptable” and “unacceptable” paths, ensuring that paths perceived as high-risk or psychologically rejected are excluded from the feasible choice set. Simulation results demonstrate that the model effectively reproduces users' risk-averse decision patterns and their impacts on the spatial and temporal evolution of network flow distributions.

At the stochastic representation level, a novel Fractional-Folding Moment Transform (FFMT) method is proposed for estimating fractional-order moments of random variables from a finite set of integer-order moments. Fractional moments provide a flexible and sensitive characterization of random processes, particularly under non-Gaussian, heavy-tailed, or long-memory distributions commonly observed in transportation systems. The FFMT method combines the Laplace transform with fractional calculus to derive both analytical and numerical expressions for fractional moments. Theoretical analyses establish explicit error bounds, parameter selection criteria, and the existence and uniqueness of optimal parameters. A short-memory principle is introduced to enhance computational efficiency. Numerical experiments verify that the FFMT method achieves superior stability and accuracy compared with traditional Taylor expansion and Monte Carlo methods, maintaining convergence even for complex and heavy-tailed distributions. This method provides a unified and efficient computational approach for representing stochastic travel time, enabling consistent information transfer between be-

havioral and optimization layers.

At the optimization level, the dissertation investigates reliable path optimization in correlated networks, focusing on both the mean–variance (m-v) and mean–standard deviation (m-s) formulations. The m-v problem, traditionally regarded as non-additive and non-linear under correlation, is reformulated as a linear programming model through the introduction of flow conservation constraints and an augmented hypergraph transformation. The constraint matrix is proven to be totally unimodular, guaranteeing the existence of integer optimal solutions and ensuring high computational efficiency. Building on this foundation, the m-s problem is formulated as a concave minimization problem, and a global optimization algorithm based on a linear programming framework is developed to ensure global optimality. Numerical results confirm that the proposed models and algorithms exhibit strong convergence, robustness, and scalability, providing a rigorous and efficient approach to reliable path optimization under correlated stochastic environments.

Through systematic integration, the three studies form a coherent and hierarchically connected mechanism. The behavioral model provides stochastic behavioral inputs, the FFMT method transforms these into measurable statistical parameters, and the reliability optimization model applies them for system-level decision-making. The proposed multi-layer framework ensures logical consistency and continuous information transfer across behavioral, stochastic, and optimization layers, enabling a unified representation of uncertainty propagation and interaction within transportation systems.

In summary, this dissertation makes theoretical and methodological contributions in three aspects: risk-sensitive behavioral modeling, fractional-moment-based stochastic representation, and reliability-oriented path optimization. The proposed framework enhances the understanding of uncertainty mechanisms in transportation networks and offers practical decision-support insights for transportation planning, disaster management, and network resilience improvement.