# Theory-based residual neural networks: A synergy of discrete choice models and deep neural networks

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Research GitHub: https://github.com/shenhao-wang/TB_ResNet.git
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# Outline

1. Background
2. Design
3. Result
4. Discussion

# 1. Background

# Classical Travel Demand Modeling - Discrete Choice Model with Utility Theory


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# DCM and DNN (glass vs. black box)

$$f: x \rightarrow y; y \in \{1, 2, \dots K\}$$

Discrete choice models
(Theory-based models)

Low prediction
High interpretability
High Robustness
…

Tension

Deep neural networks
(AI models)

High prediction
Low interpretability
Low Robustness
…



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## Research Question

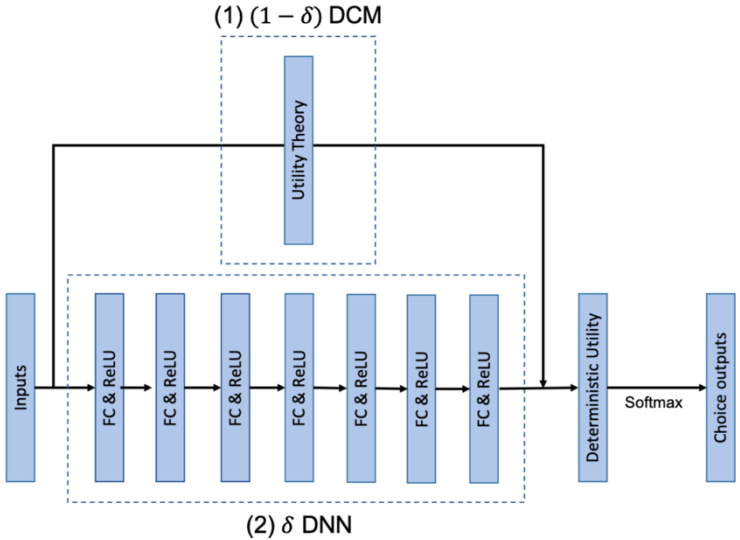
# How to synergize discrete choice models and deep neural networks to analyze individual decisions?

# 2. Design

Theory-Based Residual Neural Networks

## Theory-Based Residual Neural Network (TB-ResNet)

$$V(x) = (1-\delta)V_T(x) + \delta V_{DNN}(x)$$



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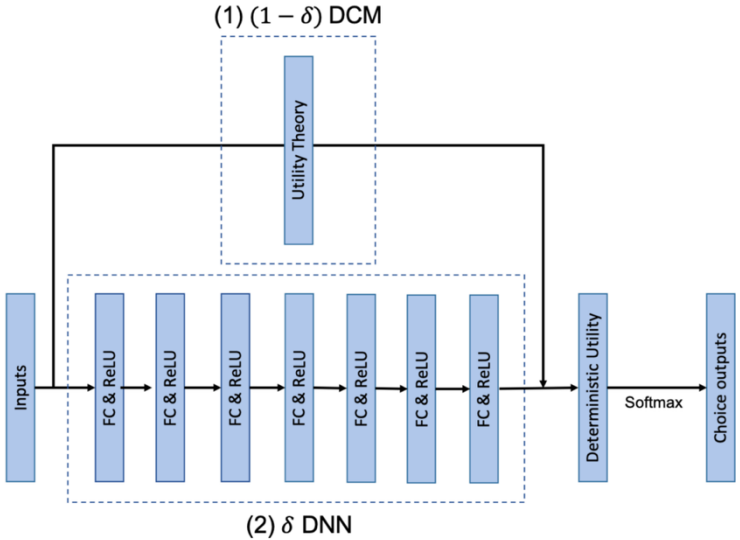
# Five Perspectives ($\delta$)

1. Weighted model ensemble
2. $\delta \to 0$, DCM dominates; $\delta \to 1$, DNN dominates
3. TB-ResNet (Analogy to ResNet)
4. $\delta$ as regularization
5. $\delta$ as theory diagnosis




$$V(x) = (1-\delta)V_T(x) + \delta V_{DNN}(x)$$



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# Three Instances of Theory-Based Residual Neural Network

**Three Instances of TB-ResNets**

$$\boldsymbol{V(x) = (1-\delta)V_T(x) + \delta V_{DNN}(x)}$$

1. MNL-ResNet (choice modeling)
   - e.g. choose between K alternatives; travel mode choice
2. PT-ResNet (prospect theory)
   - e.g. choose between two risky payoffs (x, p); travel demand under time uncertainty
3. HD-ResNet (hyperbolic discounting)
   - e.g. temporal decisions (x, t); infrastructure investment with future payoffs.



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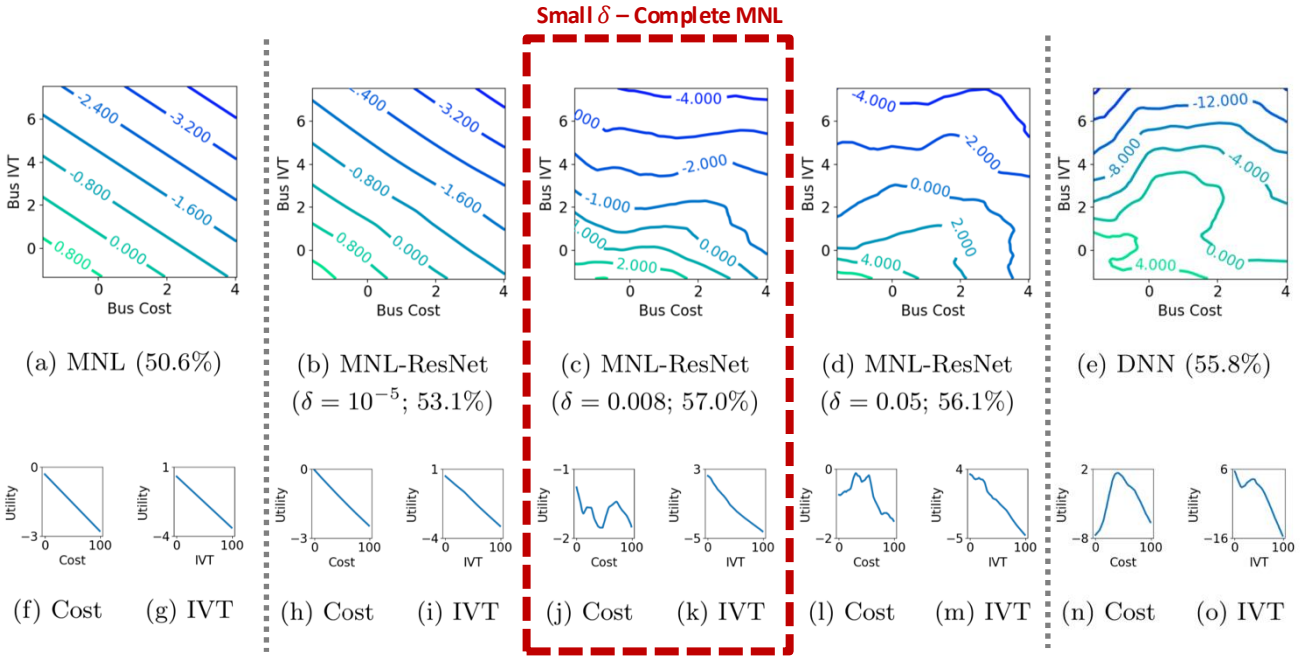
# 3. Results

Utility Interpretation, Prediction, and Robustness

# 1 – Utility Interpretability in the MNL Scenario




- DNN tends to be overly irregular while DCM tends to be overly regular in utility patterns.
- TB-ResNets strike a balance between the two ends.



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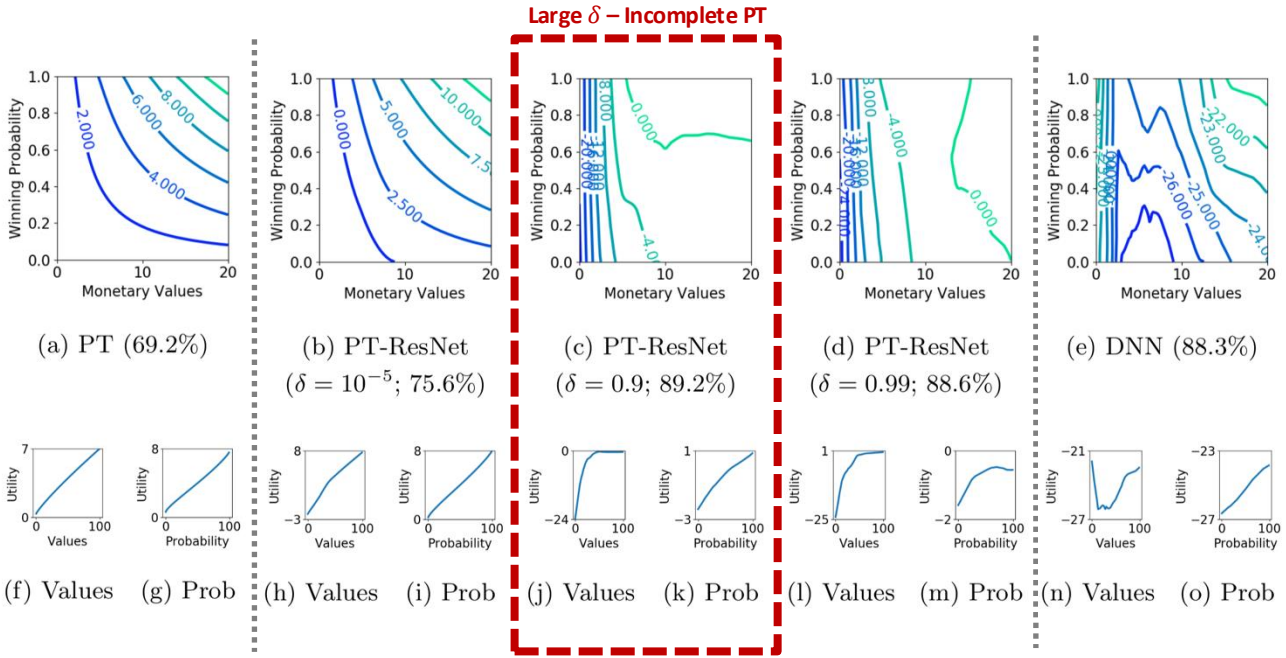
# 1 - Utility Interpretability in the PT Scenario



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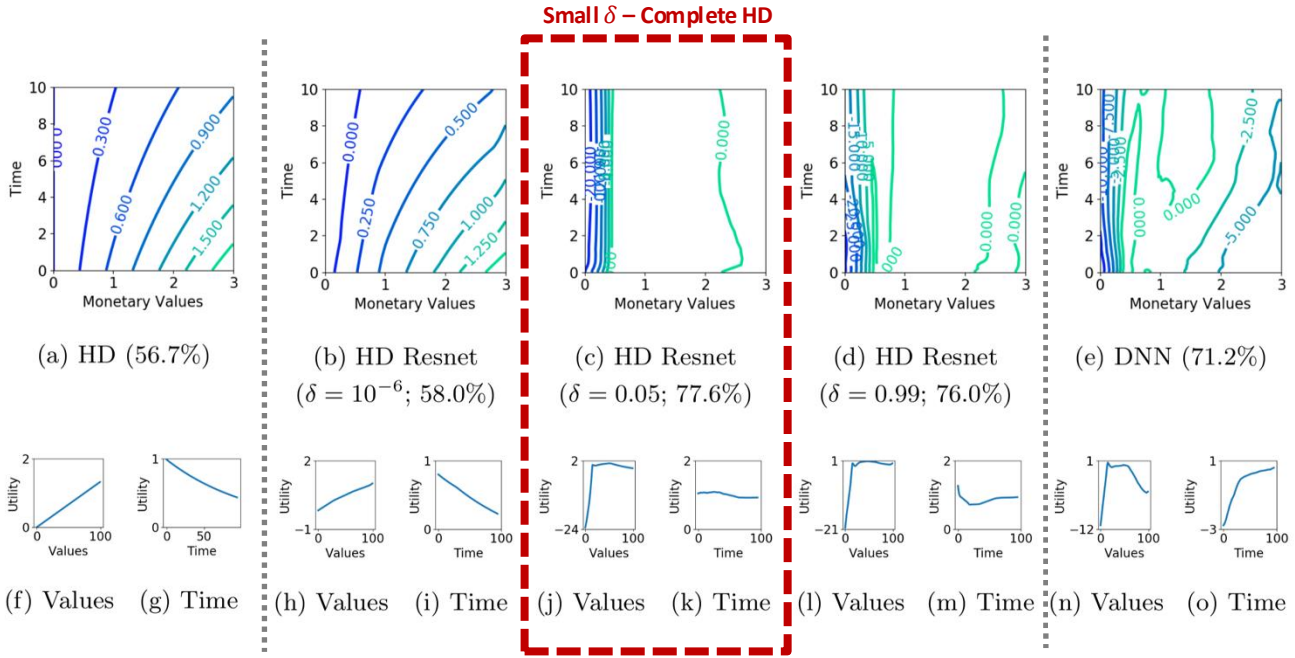
# 1 - Utility Interpretability in the HD Scenario



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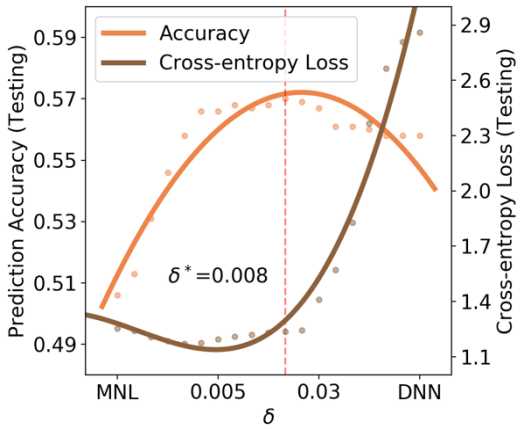
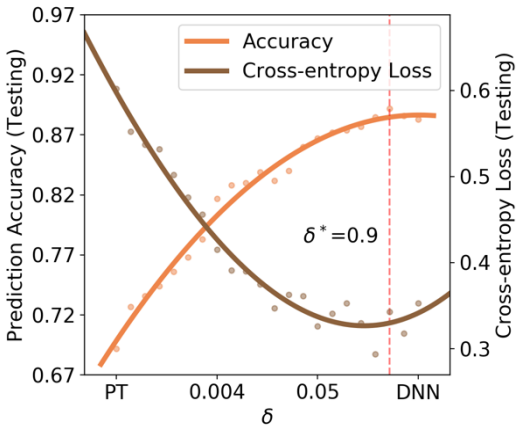
# 2. TB-ResNets address overfitting from DNN and underfitting from DCM

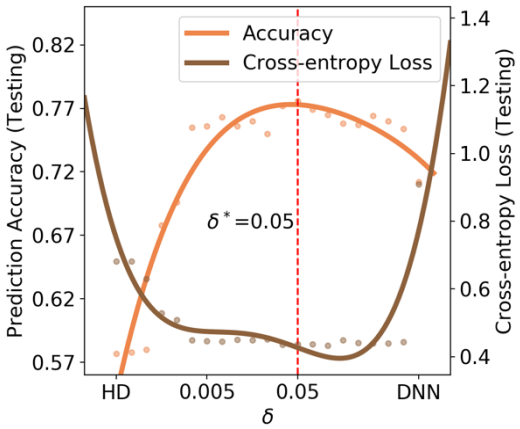
## MNL




## PT




## HD




- DNN tends to overfit the reality while DCM tends to underfit the reality.
- TB-ResNets strike a balance between overfitting and underfitting



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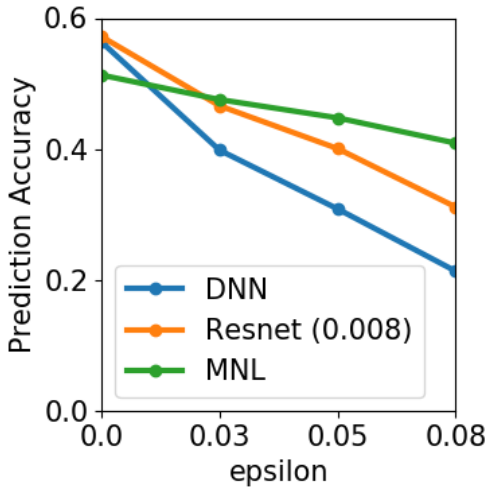
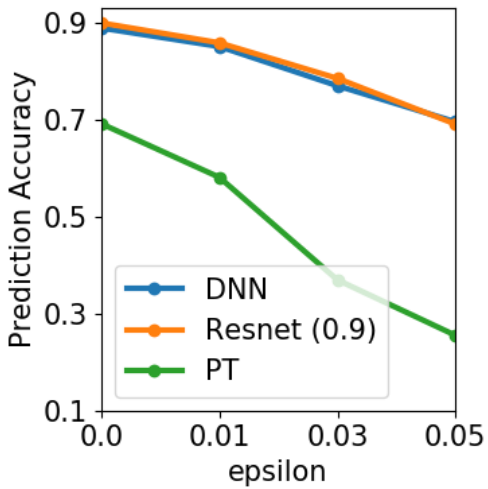
# 3. TB-ResNets improve robustness of DNNs

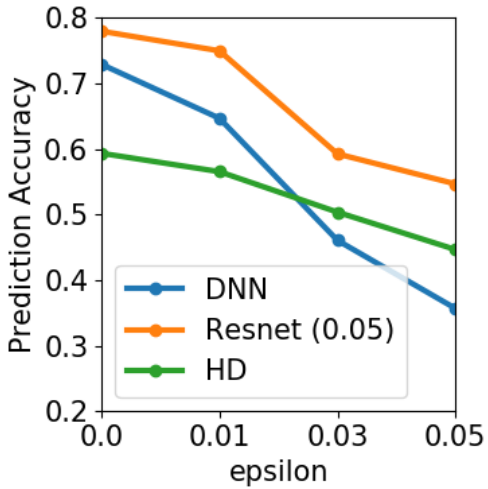
**MNL**




**PT**




**HD**




- Theory-based systems (DCM) tend to be more robust than DNN.
- TB-ResNets can improve robustness of DNN



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# Comparing TB-ResNet to DCMs and DNNs

| | Compare to DCMs (MNL, PT, and HD) | Compare to DNNs (AI Models) |
|---|---|---|
| **Prediction** | Significant **Improvement** (by addressing function misspecification) | Marginal **Improvement** (by localization and regularization) |
| **Interpretability** | Significant **Improvement** (by augmenting and enriching utility functions) | Significant **Improvement** (by stabilizing local information) |
| **Robustness** | NA | Significant **Improvement** (by stabilizing local information) |



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# Discussion

## 1 - Synergy

- Theory + AI
- Flexibility
- Interplay

## 2 - Applications

- Mobility Choice
- Urban Choice
- Economic Choice

## 3 - Future

- First Step
- Success of Synergy?



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# Thank You

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