Scaling Auctions as Insurance: A Case Study in Infrastructure Procurement

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Motivation: Scaling Auctions for Highway and Bridge Procurement

- US Infrastructure Spending

  $\Rightarrow$ 1% of GDP ($165B) on highways and bridges

- Massachusetts DOT

  $\Rightarrow$ $100 million for bridge + highway maintenance

  $\Rightarrow$ $3.7 billion backlog

- Scaling Auctions for Procurement

  $\Rightarrow$ Used by the MassDOT Highway + Bridge division for 20+ years

  $\Rightarrow$ "Bid Express" software used by 37 state DOTs

Scaling Auctions

- Gov't elicits unit bids for every "item" involved in a project
- Winner is evaluated on the sum of unit bids x DOT quantity estimates
- Winner is paid based on quantities actually used

Motivation: Worries about Bid Manipulation

The Contractors' Side

Knowledgeable contractors independently assess quantities searching for items apt to seriously underrun. By setting modest unit bids for these items they can considerably enhance the competitiveness of their total bid.

- Stark (1974)

Motivation: Worries about Bid Manipulation

The Government's Side

Bids with extreme variations from the engineer's estimate, or where obvious unbalancing of unit prices has occurred, should be thoroughly evaluated...

If the award of the contract would result in an advantage to the contractor with a corresponding disadvantage...then appropriate steps must be taken...to protect the public interest.

- Federal Highway Administration Memorandum (1988)

Motivation: Worries about Bid Manipulation

Questions:

- Is there evidence of systematic bid manipulation?
- How much does bid manipulation add to DOT costs?
- Would interventions considered by the DOT reduce costs?

MassDOT Data

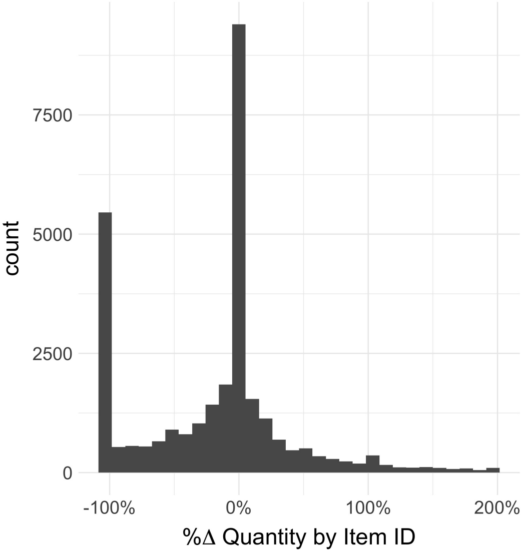
- Years: 1998-2016
- Type: Highway and Bridge, Construction and Maintenance
- Number of Projects: 440 (bridge only)
- Winning bids, losing bids, and DOT cost estimates
- Types of material, DOT quantity estimates, and amount of each material actually used
- Other information about project managers, general project location, dates of work, etc.

Summary Statistics

Statistic	Mean	St. Dev.	Pctl(25)	Median	Pctl(75)
Project Length (Estimated)	1.53 years	0.89 years	0.88 years	1.48 years	2.01 years
Project Value (DOT Estimate)	$2.72 million	$3.89 million	$981,281	$1.79 million	$3.3 million
# Bidders	6.55	3.04	4	6	9
# Types of Items	67.80	36.64	37	67	92
Ex-Post Overruns	−$26,990	$1.36 million	−$208,554	$15,653	$275,219
Extra Work Orders	$298,796	$295,173	$78,775	$195,068	$431,188

Top Bidding Firms

Distribution of Quantity Over/Under-Runs

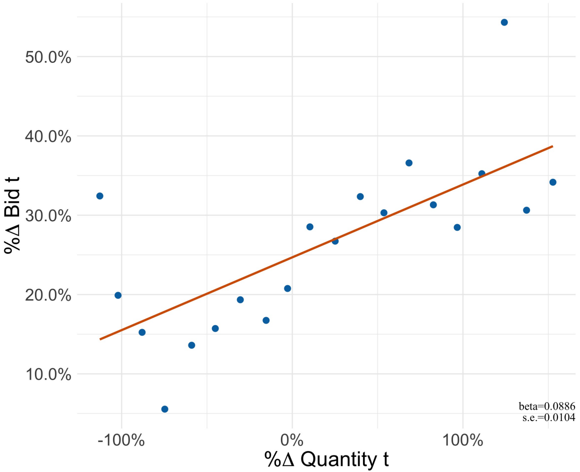


Observation 1: Items that overrun in quantity more are overbid more:

$$\uparrow \frac{q_t^a - q_t^e}{q_t^e} \Rightarrow \ \uparrow \frac{b_t - c_t}{c_t}$$

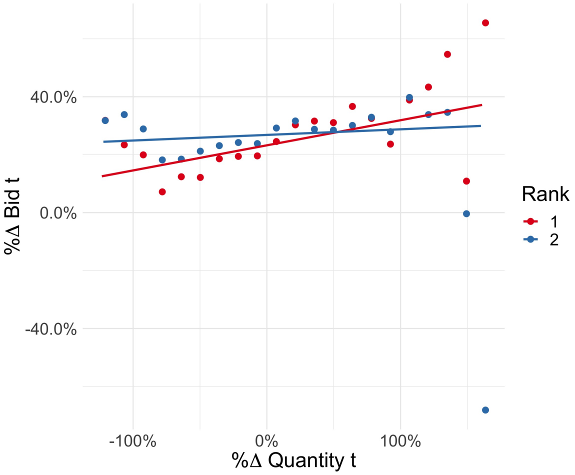
Are Massdot Bidders Better Informed?

Winning Bidders Over-Bid on Items that Over-Run



Are Massdot Bidders Similarly Informed?

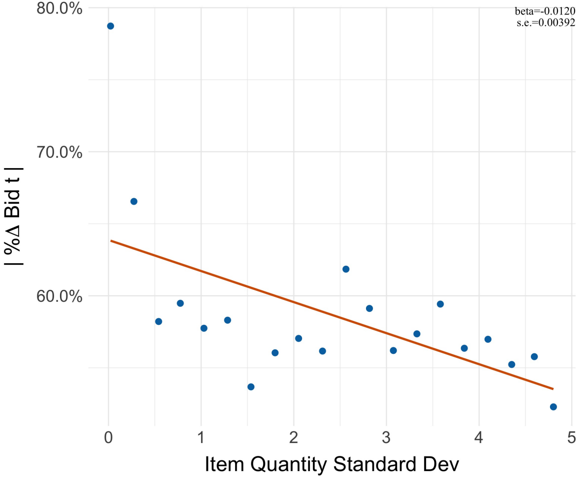
The Top 2 Bidders Over-Bid on the Same Items



▸ More Evidence

Observation 2: Items that are more uncertain have lower markups

Absolute Markups Decrease with Item Variance



▸ Details ▸ More Evidence

A Model of Bid Skewing under Risk Aversion

- Auction Observables:
  - *Ex-Ante* (Estimated) Quantities: $q_1^e, \ldots, q_T^e$
  - *Ex-Post* (Actual) Quantities: $q_1^a, \ldots, q_T^a$
  - Market-Rate Unit Costs: $c_1, \ldots, c_T$
  - Features (project manager ID, project type, etc.): X

A Model of Bid Skewing under Risk Aversion

- Information Structure:
  - Bidders get a public noisy signal of the ex-post quantity of each item:

$$q_t^b = \mathbb{E}[q_t^a | q_t^e, X]$$

$$q_t^a = q_t^b + \epsilon_t \text{ where } \epsilon_t \sim \mathcal{N}(0, \sigma_t^2)$$

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- Risk Aversion:
  - Bidders are risk averse, w/ CARA utility:

$$u_i(\pi) = 1 - exp(-\gamma\pi)$$

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$$u_i(\pi) = 1 - exp(-\gamma\pi)$$

- Efficiency Types:
  - Bidders have private "efficiency" cost types:

$$c_t^i = \alpha^i \cdot c_t \text{ for every } t$$

Bidder Profits

Each bidder i maximizes her expected utility subject to risk aversion:

$$\mathbb{E}[u(\pi(\mathbf{b}^i, \alpha^i))] = \underbrace{\left(1 - \mathbb{E}_{q^a}\left[\exp\left(-\gamma \sum_{t=1}^{T} q_t^a \cdot (b_t^i - \alpha^i c_t)\right)\right]\right)}_{\text{Expected Utility Upon Winning}} \times \underbrace{\text{Prob}\left\{s^i < s^j \text{ for all } j \neq i\right\}}_{\text{Probability of Winning}}$$

where $s^i = \sum_{t=1}^{T} b^i q_t^e$ is the score implied by $\mathbf{b}^i$.

Bidder Profits

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$$\mathbb{E}[u(\pi(\mathbf{b}^i, \alpha^i))] =$$

$$\underbrace{\left(1 - \mathbb{E}_\epsilon\left[\exp\left(-\gamma \sum_{t=1}^{T} (q_t^b + \epsilon_t) \cdot (b_t^i - \alpha^i c_t)\right)\right]\right)}_{\text{Expected Utility Upon Winning}} \times$$

$$\underbrace{\text{Prob}\left\{s^i < s^j \text{ for all } j \neq i\right\}}_{\text{Probability of Winning}}$$

where $s^i = \sum_{t=1}^{T} b^i q_t^e$ is the score implied by $\mathbf{b}^i$.

Equilibrium Bidding

1. Each α^i chooses the optimal score $s(\alpha^i)$ s.t.:

$$\frac{\partial \mathbb{E}[u(\pi(\tilde{s}, \alpha^i))]}{\partial s}\Big|_{\tilde{s}=s(\alpha^i)} = 0$$

2. For each (α^i, s), $\mathbf{b}^i$ maximizes the **certainty equivalent** of profits:

$$\max_{\mathbf{b}^i} \left[\sum_{t=1}^{T} \underbrace{q_t^b(b_t^i - \alpha^i c_t)}_{\text{Expectation of Profits}} - \underbrace{\frac{\gamma \sigma_t^2}{2}(b_t^i - \alpha^i c_t)^2}_{\text{Variance of Profits}} \right]$$

$$\text{s.t.} \ \sum_{t=1}^{T} b_t^i q_t^e = s$$

A Simple Example

- Suppose a project requires only two inputs: concrete and traffic cones

	DOT Estimates q^e	Bidders Expect q^b	Noise Var σ^2	Bidder Cost $\alpha \times c$
Concrete	10	12	2	12
Traffic Cones	20	16	1	18

Only the Total Score Matters for Winning

- The winning contractor has the lowest total bid
- Contractor's probability of winning is the same if she bids:

  a $12*10 tons + $19*20 cones = $500

  or

  b $40*10 tons + $5*20 cones = $500

Unit Bids (at a Score) Determine Profits

- The winning contractor has the lowest total bid
- Contractor's probability of winning is the same if she bids:
  a $12*10 tons + $19*20 cones = $500

  or

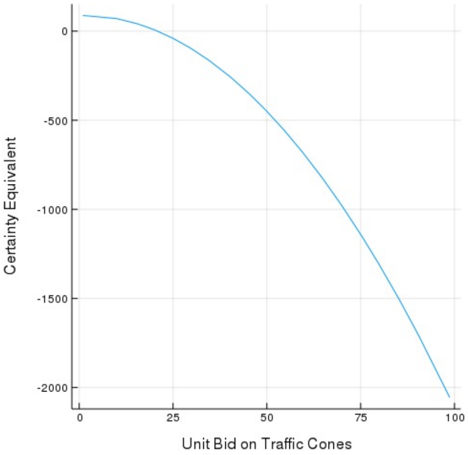
  b $40*10 tons + $5*20 cones = $500
- Contractor's expected utility upon winning is different:
  a CE($12, $19) = $15.98

  or

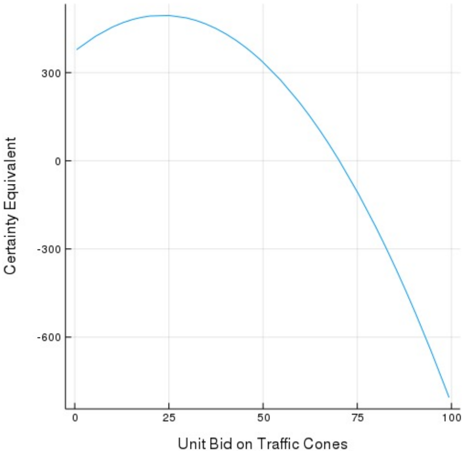
  b CE($40, $5) = $84.58

The Utility-Maximizing Bid Spread Depends on the Score

Score = \$500



Score = \$1000



Certainty Equivalents Balance Linear Profits Against Risk Variance

Score = \$1000

a $b_{\text{concrete}} = \$98$ and $b_{\text{cone}} = \$1$

$$\underbrace{12 \times (\$86) + 16 \times (-\$17)}_{\text{Expection of Profits = \$760}} - \underbrace{\frac{0.05 \times 2}{2} \times (\$86)^2 - \frac{0.05 \times 1}{2} \times (-\$17)^2}_{\text{Variance of Profits = -\$377}} = \$383$$

or

b $b_{\text{concrete}} = \$50$ and $b_{\text{cone}} = \$25$

$$\underbrace{12 \times (\$38) + 16 \times (\$7)}_{\text{Expection of Profits = \$658}} - \underbrace{\frac{0.05 \times 2}{2} \times (\$38)^2 - \frac{0.05 \times 1}{2} \times (\$7)^2}_{\text{Variance of Profits = -\$73}} = \$495$$

Math for Score = \$500

How Material is the Risk in Our Setting?
(A Structural Estimation)

Structural Model of Bidding (Overview)

- Model of optimal bidding:
  - Bidders observe a noisy signal of each item's quantity
  - Bidders are risk averse w/ common CARA utility
  - Bidders differ by a private cost-multiplier α_n^i

- Estimate parameters:
  - **Statistical model for item quantity signals**
  - Economic model of optimal bidding for
    (a) CARA Coefficient
    (b) Bidders' Cost Types

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Equilibrium Bidding

1. Each α^i chooses the optimal score $s(\alpha^i)$ s.t.:

$$\frac{\partial \mathbb{E}[u(\pi(\tilde{s}, \alpha^i))]}{\partial s}\Big|_{\tilde{s}=s(\alpha^i)} = 0$$

2. For each (α^i, s^i), $\mathbf{b}^i$ maximizes the **certainty equivalent** of profits:

$$b^*_{i,t}(s^i) = \alpha^i c_t + \frac{q^b_t}{\gamma \sigma^2_t} + \frac{q^e_t}{\sigma^2_t \sum_{p=1}^{T} \left[\frac{(q^e_p)^2}{\sigma^2_p}\right]} \left(s^i - \sum_{p=1}^{T} \left[\alpha^i c_p q^e_p + \frac{q^b_p q^e_p}{\gamma \sigma^2_p} \right] \right)$$

Detailed Assumptions

Bid Error Moment Conditions for 2nd Stage

Let $\tilde{\nu}_{t,i,n}(\theta_2|\hat{\theta}_1)$ be the demeaned bid measurement error at θ.

$$\mathbb{E}[\tilde{\nu}_{t,i,n} \cdot Z_{t,i,n}|X_{t,n}, X_{i,n}] = 0$$

where Z is each of the following instruments:

- Indicator for being a "top skewed item"
- Indicator for unique firm IDs
- The bidder-auction feature vectors that comprise $X_{i,n}$.

▸ Model Fit ▸ Estimation Results

Constructing a Counterfactual Scaling Auction Equilibrium

- Data: $\{q^e_{t,n}\}$, $\{q^a_{t,n}\}$, $\{c_{t,n}\}$, X_n
- First Stage Estimates: $\{\widehat{q^b_{t,n}}\}$, $\{\widehat{\sigma^2_{t,n}}\}$
- Second Stage Estimates:
  - Estimated CARA Coefficient: $\widehat{\gamma} = 0.046$
  - IID Parametric Fit for Distribution of Bidder Type Estimates:

$$\widehat{\alpha^i_n} \sim \text{LogNormal}(\mu^\alpha_n, {\sigma^\alpha_n}^2)$$

Equilibrium Bidding Solution

1. Each α^i chooses the optimal score $s(\alpha^i)$ s.t.:

$$\frac{\partial \mathbb{E}[u(\pi(\tilde{s}, \alpha^i))]}{\partial s}\Big|_{\tilde{s}=s(\alpha^i)} = 0$$

2. For each (α^i, s), $\mathbf{b}^i$ maximizes the **certainty equivalent** of profits:

$$\max_{\mathbf{b}^i} \left[\sum_{t=1}^{T} \underbrace{q_t^b (b_t^i - \alpha^i c_t)}_{\text{Expectation of Profits}} - \underbrace{\frac{\gamma \sigma_t^2}{2} (b_t^i - \alpha^i c_t)^2}_{\text{Variance of Profits}} \right]$$

$$\text{s.t. } \sum_{t=1}^{T} b_t^i q_t^e = s \text{ and } b_t^i \geq 0$$

Alternative Mechanisms: Pre-Committing to Quantities

- Suppose that the DOT pays the winning bidder based on the DOT quantities

  $\Rightarrow$ This is essentially a "lump sum" auction

Lump Sums Shift Risk onto Bidders

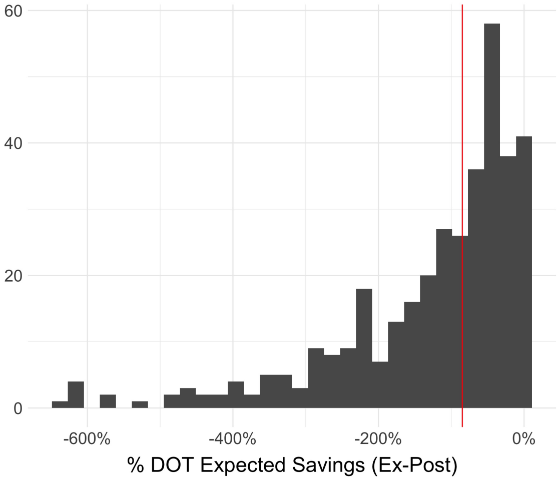
- Bidders' Certainty Equivalent under Lump Sum

$$\sum_t (b_t q_t^e - \alpha c_t q_t^b) - \underbrace{\frac{\gamma \sigma_t^2}{2} \cdot (\alpha c_t)^2}_{\text{Variance Term}}$$

- Bidders' Certainty Equivalent under Scaling Auction

$$\sum_{t=1}^{T} (b_t q_t^b - \alpha c_t q_t^b) - \underbrace{\frac{\gamma \sigma_t^2}{2} (b_t - \alpha c_t)^2}_{\text{Variance Term}}$$

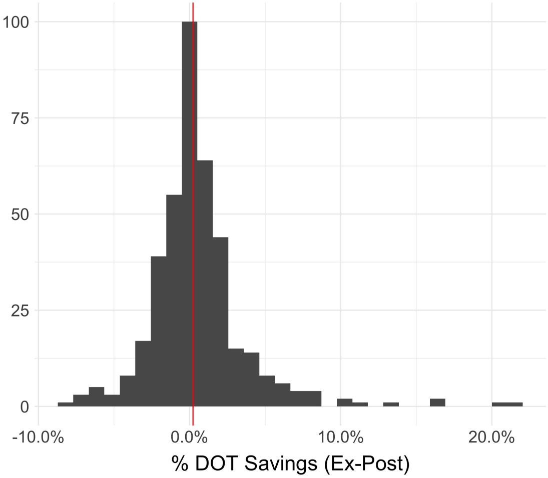
The DOT Spends More Under Lump Sum Risk-Sharing



Counterfactual: Eliminating Risk

- Baseline:
  - Status Quo DOT Quantity Estimates: $q^e_{t,n}$
  - Estimated Bidder Quantity Prediction: $\widehat{q^b_{t,n}}$
  - Estimated Quantity Variance: $\hat{\sigma}^2_{t,n}$
- No Risk:
  - Perfect DOT Quantity Estimates: $q^e_{t,n} = q^a_{t,n}$
  - Perfect Bidder Quantity Prediction: $q^b_{t,n} = q^a_{t,n}$
  - Zero Quantity Noise: $\sigma^2_{t,n} = 0$

The DOT May Not Save Much, Even Eliminating All Uncertainty

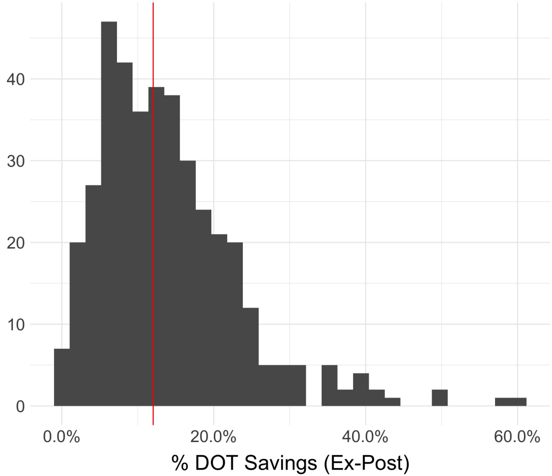


Histogram in Dollars

Counterfactual: Eliminating Risk w/o Bidder Mis-Prediction

- **Modified Baseline:**
  - Status Quo DOT Quantity Estimates: $q^e_{t,n}$
  - **Estimated Bidder Quantity Prediction:** $\mathbf{q^a_{t,n}}$
  - Estimated Quantity Variance: $\hat{\sigma}^2_{t,n}$
- No Risk:
  - Perfect DOT Quantity Estimates: $q^e_{t,n} = q^a_{t,n}$
  - Perfect Bidder Quantity Prediction: $q^b_{t,n} = q^a_{t,n}$
  - Zero Quantity Noise: $\sigma^2_{t,n} = 0$

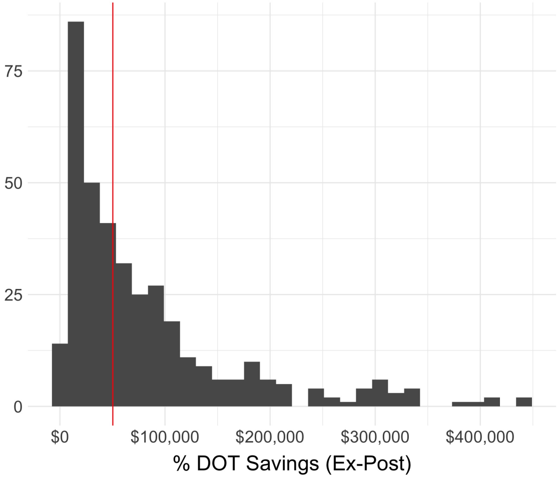
DOT Savings from Eliminating Risk are High when Bidders Guess Right



▸ Histogram in Dollars

Potential Gains from Increased Competition

DOT Savings From an Additional Entry



Summary Stats

A Model of Entry Costs

For each prospective bidder:

- Bidder arrives
- Observes public auction characteristics + entry cost
- Decides whether or not to participate
- If she participates:
  - Observes private type α
  - Chooses optimal unit bids according to equilibrium strategy

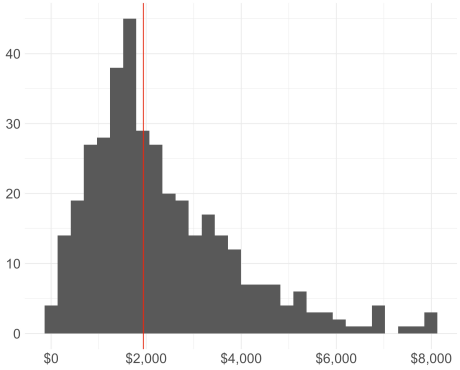
Bounds for Entry Costs

- The number of bidders that participate is set in equilibrium:

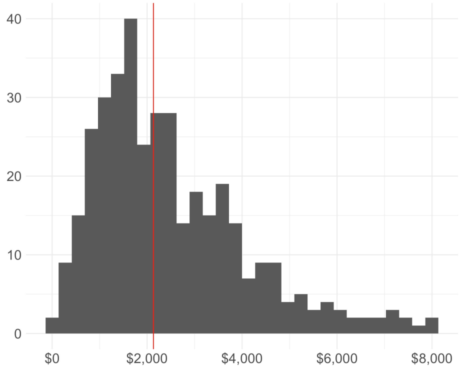
$$E[u(\pi(N^*) - K)] \geq 0 \geq E[u(\pi(N^* + 1) - K)]$$

where $E[u(\pi(N) - K)]$ is the ex-ante expected utility of participating in an auction w/ N bidders given an entry cost K

Bounds for Entry Costs



Lower Bound



Upper Bound

Conclusion

- Bidders are sophisticated & skew to maximize profits
  - ⇒ But skewing does not necessarily raise DOT costs
- Scaling auctions are particularly useful in this setting
  - ⇒ They form insurance to risk averse bidders by a party that can control moral hazard
- Policy should focus away from skewing and toward competition
  - ⇒ Entry costs may not be very hard to subsidize
  - ⇒ But an additional competitor can drive substantial savings to the DOT

Thank You

Thank You!

Estimating A Model of Quantity Uncertainty

For each item t in auction n:

- Predict best-fit of ex-post quantity given:
  - DOT estimate $q^e_{t,n}$
  - Item-Auction Features $X_{t,n}$
- Estimate using Hamiltonian Monte Carlo
- Output:
  - Predicted quantity: $\widehat{q^b_{t,n}}$
  - Residual variance: $\hat{\sigma}^2_{t,n}$

Details Model Fit Back

Certainty Equivalents Balance Linear Profits Against Risk Variance

a $b_{\text{concrete}} = \$12$ and $b_{\text{cone}} = \$19$

$$\underbrace{12 \times (\$0) + 16 \times (\$1)}_{\text{Expection of Profits}} - \underbrace{\frac{0.05 \times 2}{2} \times (\$0)^2 - \frac{0.05 \times 1}{2} \times (\$1)^2}_{\text{Variance of Profits}} = \$15.98$$

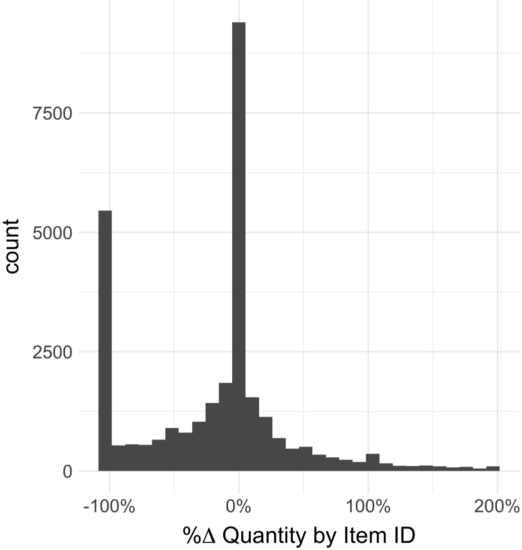
or

b $b_{\text{concrete}} = \$40$ and $b_{\text{cone}} = \$5$

$$\underbrace{12 \times (\$28) + 16 \times (-\$13)}_{\text{Expection of Profits}} - \underbrace{\frac{0.05 \times 2}{2} \times (\$28)^2 - \frac{0.05 \times 1}{2} \times (-\$13)^2}_{\text{Variance of Profits}} = \$84.58$$

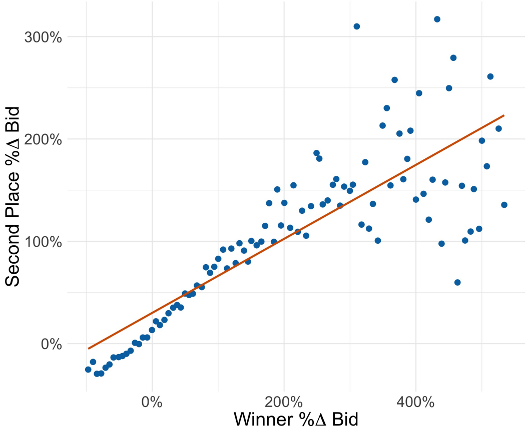
Math for Score = $1000

Distribution of Quantity Over/Under-Runs



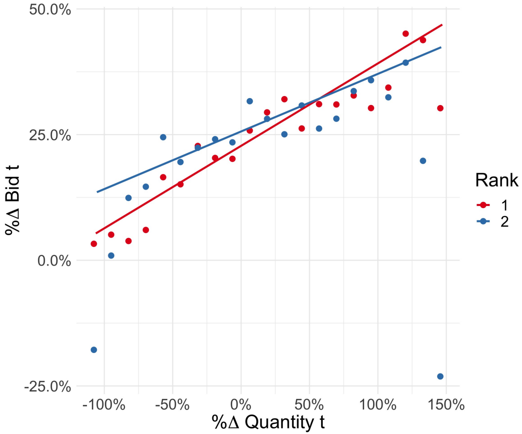
Back

The Top Two Bidders Bid Similarly on Average



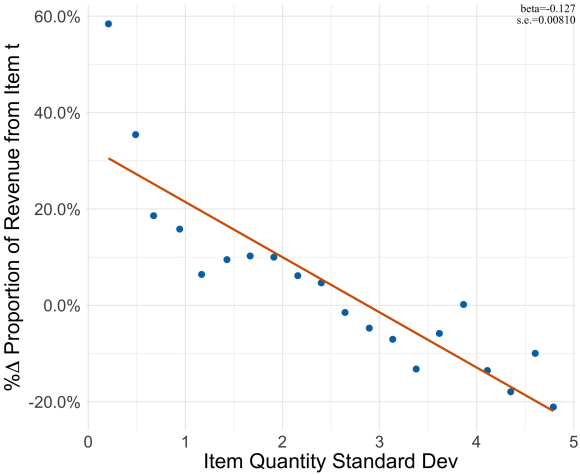
Back to Bidder Comparison

Top Two Bids are Especially Close on Items that Don't Go Unused



Back to Bidder Comparison

The Proportion of Revenue from each Item Decreases with its Variance



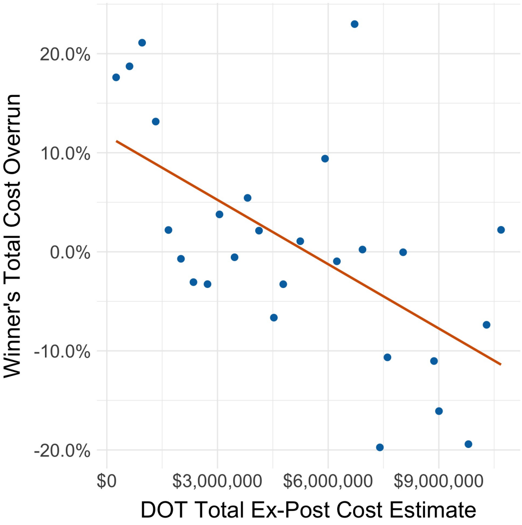
▸ Definition ▸ More Evidence ◂ Back

Bid Revenue Proportion Definition

$$\%\Delta \text{ Proportion Revenue from } t = \frac{\frac{b_t q_t^a}{\sum_p b_p q_p^a} - \frac{c_t q_t^e}{\sum_p c_t q_p^e}}{\frac{c_t q_t^e}{\sum_p c_t q_p^e}} \times 100$$

Back to Bin Scatter

Ex-Post Overruns are Lower for Higher Value Projects



Back to Rev Proportion Scatter

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- Output:
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  - Residual variance: $\hat{\sigma}^2_{t,n}$

Back Details Model Fit

Estimation: Quantity Signal Model

$$q^a_{t,n} = \beta_{0,q} q^e_{t,n} + \vec{\beta}_q X_{t,n} + \eta_{t,n}$$

where

$$\eta_{t,n} \sim \mathcal{N}(0, \hat{\sigma}^2_{t,n})$$

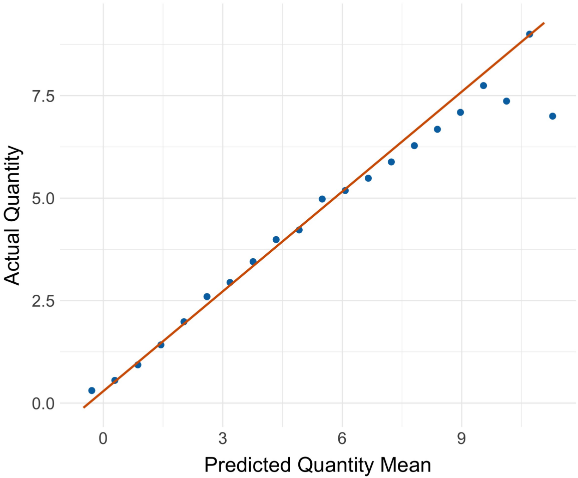
and

$$\hat{\sigma}_{t,n} = \exp(\beta_{0,\sigma} q^e_{t,n} + \vec{\beta}_\sigma X_{t,n}).$$

Back to Quantity Model Overview

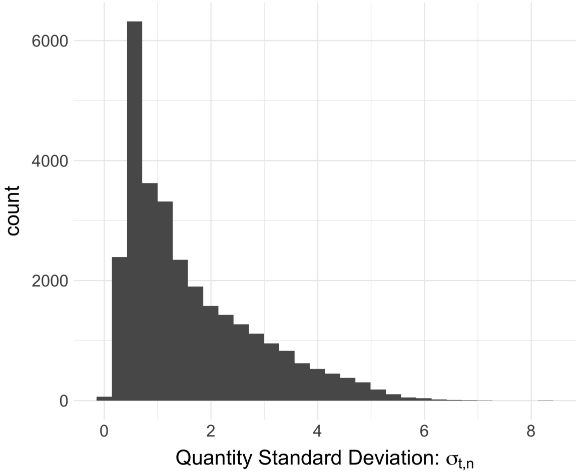
Quantity Signal Model Prediction Fit

Predicted Item Quantities Against Realized Quantities (Bin Scatter)



Back to Quantity Model Overview

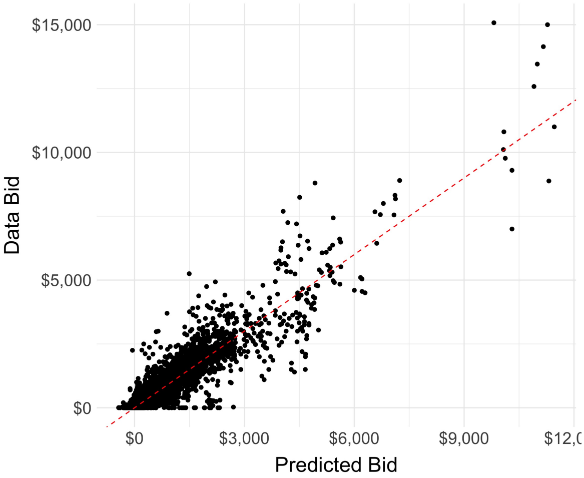
Quantity Signal Model Residual Standard Deviations



Back to Quantity Model Overview

Second Stage Model Fit

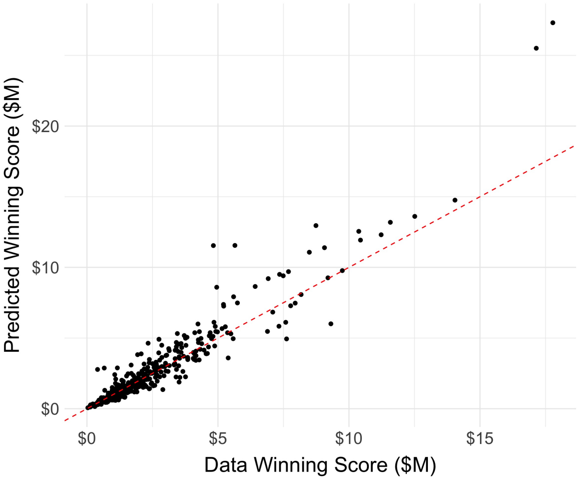
Predicted Bids Against Actual Bids



▸ Back to Results

Equilibrium Model Fit

Predicted Winners' Scores Against Actual Scores



Back to Results

Risk Aversion + Cost Type Estimates

$\widehat{\gamma}$	95% CI
0.046	(0.032,0.264)

		$\widehat{\alpha}_n^i$			
Project Type	Mean	St Dev	25%	**Median**	75%
All	0.975	0.261	0.822	**0.949**	1.139
Bridge Reconstruction/Rehab	1.019	0.25	0.85	**1.005**	1.225
Bridge Replacement	0.996	0.219	0.855	**1.009**	1.159
Structures Maintenance	0.919	0.312	0.782	**0.873**	0.978

Ex-Post Mark-Ups

Summary statistics of estimated winning bidders' markups given $\hat{\alpha}_n^i$

Project Type	Mean	Bidder Markups			
		St Dev	25%	**Median**	75%
All	17.03%	60.88%	-12.84%	**5.74%**	27.53%
Bridge Reconstruction/Rehab	11.39%	35.88%	-15.61%	**7.34%**	23.07%
Bridge Replacement	12.8%	67.43%	-12.34%	**1.43%**	23.67%
Structures Maintenance	23.9%	62.12%	-9.66%	**10.56%**	39.13%

Back to Moment Conditions

Assumptions

- Bidder i's costs are fully characterized by a 1-D type α^i s.t.

$$c_t^i = \alpha^i c_t^o \text{ for all } t.$$

- All bidders have *the same* coefficient of absolute risk aversion γ
- All bidders observe *the same* vector of quantity signals $\{q_t^b\}_{t=1,\dots,T}$
- Bidders have common, rational expectations over the distributions of quantity signals + scores
- The number of bidders is commonly known prior to bidding

▸ Optimal Bid Program ◂ Auction Characterization

Equilibrium Bidding

1. Each α^i chooses the optimal score $s(\alpha^i)$ s.t.:

$$\frac{\partial \mathbb{E}[u(\pi(\tilde{s}, \alpha^i))]}{\partial s}\Big|_{\tilde{s}=s(\alpha^i)} = 0$$

2. For each (α^i, s), $\mathbf{b}^i$ maximizes the **certainty equivalent** of profits:

$$\max_{\mathbf{b}^i} \left[\sum_{t=1}^{T} \underbrace{q_t^b (b_t^i - \alpha^i c_t)}_{\text{Expectation of Profits}} - \underbrace{\frac{\gamma \sigma_t^2}{2} (b_t^i - \alpha^i c_t)^2}_{\text{Variance of Profits}} \right]$$

$$\text{s.t.} \sum_{t=1}^{T} b_t^i q_t^e = s$$

▸ Auction Characterization

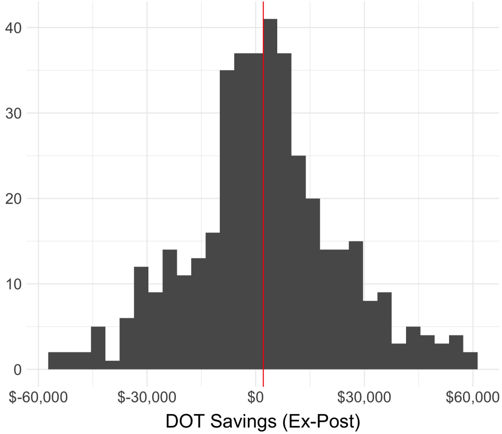
Certainty Equivalents by Scale for $\widehat{\gamma} = 0.046$

Prize	Prize for 50-50 to Equal 50%	Certainty Equivalent for 50-50 Bet to Win/Lose Prize Value
1	1	0
10	10.001	-0.002
100	100.115	-0.23
1,000	1,011.771	-22.992
10,000	11,504.674	-2,223.188

Estimation Results

Counterfactual: What if We Eliminate Risk?

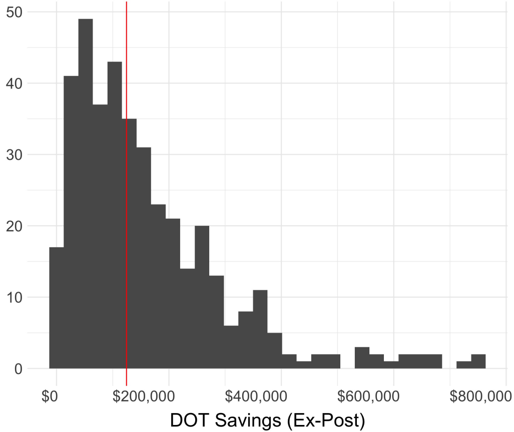
DOT Savings in Dollars



▸ Histogram in Percent

Removing Bidder Mis-Estimation in the Baseline

DOT Savings from Eliminating Risk



▸ Histogram in Percent

Counterfactual: What if We Eliminate Risk?

Baseline

Statistic	Mean	St. Dev.	25%	Median	75%
Net DOT Savings	\$2,145.37	\$24,704.09	− \$9,354.61	\$2,203.49	\$13,987.89
% DOT Savings	0.70%	4.25%	−1.02%	0.23%	1.60%
Bidder Gains	\$6.64	\$145.87	\$3.76	\$17.61	\$43.35

$$\mathbf{q_t^b = q_t^a}$$

Statistic	Mean	St. Dev.	25%	Median	75%
Net DOT Savings	\$172,513.80	\$165,129.50	\$61,569.34	\$125,187.10	\$226,318.90
% DOT Savings	13.74%	9.05%	7.18%	11.98%	18.25%
Bidder Gains	\$19.16	\$124.55	−\$8.48	\$4.81	\$37.64

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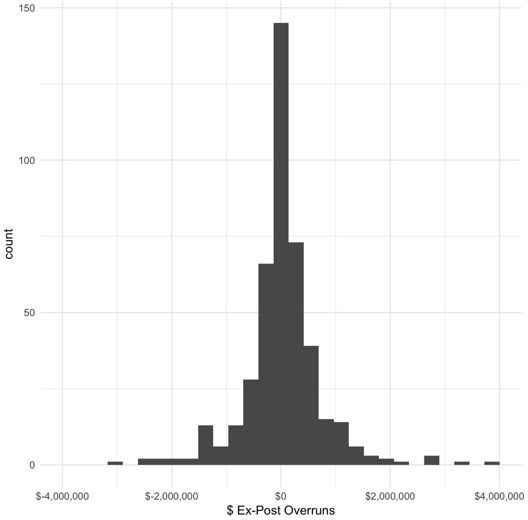
Summary Statistics

Statistic	Mean	St. Dev.	Pctl(25)	Median	Pctl(75)
Project Length (Estimated)	1.53 years	0.89 years	0.88 years	1.48 years	2.01 years
Project Value (DOT Estimate)	$2.72 million	$3.89 million	$981,281	$1.79 million	$3.3 million
# Bidders	6.55	3.04	4	6	9
# Types of Items	67.80	36.64	37	67	92
Ex-Post Overruns	−$26,990	$1.36 million	−$208,554	$15,653	$275,219
Extra Work Orders	$298,796	$295,173	$78,775	$195,068	$431,188

Ex-Post Overruns (Data)



Summary Statistics

Counterfactual: What if an Additional Bidder Enters?

Statistic	Mean	St. Dev.	25%	Median	75%
Net DOT Savings	$82,583.25	$87,568.51	$22,296.89	$49,335.35	$103,379.50
% DOT Savings	8.90%	8.45%	2.06%	5.65%	13.47%
Bidder Certainty Equivalent	$2,315.80	$1,524.88	$1,264.95	$1,959.42	$3,135.44

Back to Histogram