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Essays on Incentive Mechanisms in Procurement Auctions

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ESSAYS ON INCENTIVE MECHANISMS
IN PROCUREMENT AUCTIONS

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ABSTRACT

Highway construction projects serve as a good example where society can benefit from fast completion. A+B auctions, a type of innovative scoring auctions, address this concern by incentivizing timely completion through scores that combine price and time incentives. In the first part of the dissertation, I investigate in A+B auctions by building a theory of A+B bidding that incorporates incentives and production uncertainty, as well as structurally estimating bidding behaviors and auction performance using data from the California Department of Transportation (Caltran). I find that, in equilibrium, bidders skew the days bid below the true planned construction target days to raise the price bids. Moreover, self-selected construction time that is different from the expected social-optimal time causes *ex post* efficiency loss and the auction mechanism can fail at picking the socially-efficient bidders *ex ante.* Counterfactual analysis suggests that procuring schemes with lower incentives or even conversion back to traditional contracts are likely to yield better social outcomes.

Usually, highway procurement auctions across the U.S. take the form of Unit-Price Contracts (UPCs), where the department of transportation (DOT) gives quantity estimates for different tasks of the project and the bidders attach unit-price bids on each of the tasks and form a single total bid. During the construction phase, the DOT makes progress payments, usually monthly, to the contractor for tasks completed in the previous month. Moreover, the payments are determined by the actual quantities incurred although the total bids *ex ante* are evaluated based on the DOT estimates. A forward-looking contractor would want to maximize the expected total present value by shifting more

weight toward early tasks and tasks that the bidders believe to overrun compared to the DOT estimates. These two types of bid skewing lead to what is generally known in the industry as “unbalanced bids”, which I empirically test and quantify in the second part of the dissertation.

DEDICATION

I would like to dedicate this dissertation to my parents who have always loved me and supported me unconditionally.

I also dedicate this dissertation to my advisors Daniel Miller, Tom Chungsang Lam, Matthew Lewis, and Andrew Hanssen. Thank you so much for the continuous guidance throughout my years of graduate study. You have always been more than the mentors that I could ask for!

Finally, I would like to express my gratitude to Chaoren, who cares and helps me generously along the way. You inspire me every day.

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CHAPTER ONE

INCENTIVE MECHANISMS IN "COST + TIME" AUCTIONS

1 Introduction

In highway construction industry, the uniqueness of the projects, transparency and private information of costs give rise to auctions being the means of buying projects. Traditional bidding methods (where bidders bid on project costs only), however, do not address the concerns beyond taxpayers' bucks, thus no competition over completion time or other dimensions of quality is allowed. Over decades, many efforts have been spent on discovery of innovative procurement methods. Among the industries, highway construction makes for a good case study for this is an industry where huge amounts of externalities for commuters are observed in terms of traffic delay caused by construction on the road.[1]

In 1991, the Federal Highway Administration recommended that the departments of transportation (DOTs) around the U.S. start to experiment with a novel bidding

[1]The example used in Lewis and Bajari(2011a) gives readers some idea on the magnitude of the externalities. "For example, US 101 is an important highway through Silicon Valley, carrying over 175,000 commuters per day. If a highway construction project results in a 30-minute delay each way for commuters on this route, the daily social cost imposed by the construction would be 175,000 hours. Valuing time at $10 an hour, this implies a social cost of $1.75 million per day."

mechanism which they called A+B, or 'cost plus time'. 'A' stands for the traditional dollar amount of the bid, and 'B' is the public cost of the project, which is the per-day road user cost (government-assessed dollar-amount externality of construction work to commuters) multiplied by the number of days bid by contractors. A+B gives the score, and the contractor with the lowest score wins the auction and gets paid by A when the construction completes. In the case of late delivery, penalty gets excercised which is usually the amount of per-day user cost times the number of days the contractor is late by (construction days minus the days bid in the score). These innovative contractual formats were tried in several states and then gradually gained popularity across America over the last few decades. Today, almost all of the DOTs are adopting A+B or some variants of A+B (Strong, Raadt and Tometich(2006)).

Clearly, the monetary incentive in the score is intended to incentivize contractors to speed up construction when it is cost-effective to do so. This is made possible by the design of the scoring rule which creates tradeoffs between price bids and time bids: holding the score (thus the chance of winning) constant, bidders can either choose a high price and tight schedule, or a long duration and fewer bucks. Bidders' actual opportunity costs of being late, though, might be higher than, equal to, or lower than the explicit monetary incentives layed out in the scores for various reasons. What is equally plausible is bidders' heterogeneity in these opportunity costs. Thus discussion of bidder optimality cannot be made complete or credible without recognizing both the monetary incentives and the opportunity costs.

Construction uncertainty is well-aknowledged in highway construction industry. Construction time, or the duration of the project, is a simultaneous result of contractors' optimization outcome, contractor-project shocks (e.g. input delays, malfunctioning equipments, bad progress plan and execution) as well as nature's work (some idiosyncratic shocks that are beyond contractors' control, such as weather, local events, earthquakes). A contractor, facing a great deal of uncertainty once the production begins, would incorporate this uncertainty in her bidding and planning decisions at the bid-preparing stage, and this may be even more relevant when high-powered incentive and disincentives come into play in A+B auctions. With uncertainty as one extra layer of the complex procuring problem, effective policy design is of an even greater importance and much more discretion is needed in analyzing the underlying mechanism of private bidding behaviors.

In this paper, I investigate in the efficiency and effectiveness of A+B procuring mechanism featuring both incentives and production uncertainty. I first incorporate production uncertainty into a theory of equilibrium bidder behavior in an A+B contracting environment. I characterize the equilibrium bidding behavior and discuss the efficiency of A+B mechanism. Second, I provide descriptive and reduced-form evidence that is consistent with the theory predictions. Next, I carry out a structural analysis on the performance of A+B auctions under uncertainty. Last, I evaluate the advantages and disadvantages of the current A+B contract design based on the empirical evidence and through the construction of counterfactual alternatives.

I find that bidders strategically skew their bids—when the underlying opportunity cost is too high compared to the monetary incentive, bidders find it optimal to bid conservatively, i.e., the time bid would be greater than their planned construction time to leave some contingency time in light of heavy penalties. On the other hand, when the opportunity cost of being late is relatively mild, bidders would bid aggressively by shading their time bid under the planned construction days since doing this will push up the price part while holding the score constant. And this latter case is what my empirics supports.

I demonstrate that current A+B policy is sub-optimal in that it is both ex-post inefficient and ex-ante inefficient. Once uncertainty is built into the model, bidders' behaviors most likely deviate from the first-best point. In particular, my structural estimation shows that the contracting environment is such that most bids observed are well below the true construction target time of bidders. As long as costs are convex with respect to time, different target times other than the first-best points mean welfare loss to society. Furthermore, bid skewing may also lead to ex-ante inefficiency due to the possible wrong rank order of bidders and hence inability of the auction mechanism to assign the project to the most socially efficient bidder.

I provide evidence and support for converting the current A+B provision to a more 'low-powered' incentive framework or even back to traditional bidding through the construction of counterfactuals. Based on the estimates of the structural elements, varying the policy parameter (coefficient in B part) does bring down the actual target time as well as the bid days, but the bid skewing pattern remains with similar magnitude. As incentives are made stronger, Caltran's payments (price bids of winners) increase more than commuters' welfares gain. Combining the considerations of commuter welfare, private construction cost, and government budget, I argue for procuring schemes with lower incentives than current or even conversion back to traditional contracts. And this policy implication is direct and intuitive since under current framework, bidders' actual construction behaviors are indeed not much different than what they would have been had the projects procured the traditional way.

To my knowledge, this is the first paper so far that tries to structurally investigate in A+ B procurement auctions featuring both uncertainty and incentives. Lewis and Bajari (2011a) is the first analysis of A+B auctions by economists. The find that A+B successfully aligns private interests with public ones and both *ex-ante* and *ex-post* efficiency can be achieved, however this finding essentially builds upon the crucial assumption of construction certainty and may overlook the possible skewing behaviors of bidders who balance uncertainty and incentives. And this naturally leads to welfare calculations of theirs dramatically differ than mine.

The findings in this paper may also contribute to the classical principle-agent problem with detailed analysis of field data on auctions. Well-known works such as Holmstrom and Milgrom (1991) stresses on the importance to analyze incentive problems in their totality. And this paper provides real-world evidence and extends our knowledge on how certain contractual designs collapse when incentives and risk are incorrectly and incompletely addressed. Lewis and Bajari (2013) demonstrate how incentives and risk can affect *ex-post* work rate in highway procurements by focusing on traditional contracts, and they find evidence of post-contractual moral hazard. The striking difference of this paper, though, is the discovery of *ex-ante* distortions once integrating incentive design, risk and bidding rules into bidders *ex-ante* optimization.

This paper is closely related to the emerging literature of theoretical and empirical scoring auctions. Theories such as Che(1993), Asker and Cantillon(2008) give rigorous treatments on and analyze properties of scoring auctions. Empirical studies such as Athey and Levin (2001), Bajari, Houton and Tadalis(2014), Miller(2014) investigate in contractual environments where submitted bids are inner products of quantities and unit prices and they elaborate on bidders' bid skewing behaviors. In my paper, the aggressive bidding is essentially bid skewing, too, with two dimensions instead of many to skew along—price and days bid.

The paper is organized as follows. Section 2 gives a description of the background and contractual environments of A+B auctions, and also points out the key features of A+B procurements. Section 3 presents a theory of A+B bidding with incentives and uncertainty. Section 4 discusses the data and provides descriptive evidence. Section 5 presents the structural estimation. Section 6 conducts policy analysis and performs counterfactual investigations. Section 7 concludes.

2 A+B highway procurement projects in California

With the purpose of promoting welfare to traveling public by reducing commuting time in work zones, the California Department of Transportation started to encourage the use of A+B contracts on highway procurement in late 2002. According to the Caltran "Guidelines for Use of A+B Bidding Provisions", "A+B provisions should be included in projects meeting selection criteria including estimated cost of $5 million or more and daily user delay cost of $5,000 or more", although exceptions to the criteria can be made.

Usually, the implementation of A+B projects in California goes through several phases. First, the engineers at Caltrans design the project once a need is identified. The engineers come up with 3 estimates: an estimate of the cost of the project, the per-day user delay cost and an estimate of the time of project delivery. Usually the engineer estimated days is a generous measure of completion time hence any bids on the B part exceeding the engineer days estimate would be rendered irresponsive and will not be considered by Caltran.[2] The terms of the contract are summarized in the project special provision and its addendums. The special provision specifies that the contract will be awarded to the bidder with the lowest score and the winner have to deliver the project within its days bid. If late completion takes place, penalties are charged. A majority of the contents are dedicated to various construction specifications. What is also included is a set of specifications on maximum number of lanes that can be closed at each phase of the projects, whether there are and how much the penalties are if lanes are reopened late than specified and so on.

[2]Actually, Caltran specifically mentions in the "Guidelines for Use of A+B Bidding Provisions" that "On typical A+B projects, working days are defined...the same as for traditional projects."

Next, the project gets advertised and interested parties can obtain information of the plan and special provisions. Before bidding and after advertisement, Caltran might find the need to issue one or multiple addendums that supplement the original special provision. And the provision and its addendums together constitute the legal contract between Caltran and the auction winner. After studying and evaluating the project specifications and addendums, bidders bid on the contract, according to the scoring rule specified in the contract. Then Caltran opens bidding results and announces the winner. Then, the contract is awarded to the bidder with the lowest score[3] and the phase of construction begins. At the start of construction phase, the winning contractor decides on the amount of capital equipments and man power that go into the production. Throughout the production process, shocks take place and affect the planned schedule. During the whole phase of construction, the project engineer conducts random checks on quality and schedules, meanwhile the performance of the contractor is recorded and progress payments are made to the contractor.

Last, after the project is finished, the contractor gets paid the amount they bid less the progress payments over the construction phase as well as any damages occurred for late completion.

Usually the contractor plans the project schedule with sophisticated computer softwares using Critical Path Method (CPM) that basically groups activities into critical-path activities and off-path activities. Activities on the path are critical at influencing the pace of the project, while off-path activities can give the contractor some time slack. Thus any shock to the earlier activities would likely result in

[3]Normally after announcement, losers of the auction can have bid protests against the winner, by showing evidence to Caltran of the winner's violation of bidding rules or incapability of performing the work. If protests are supported by Caltran, project goes to next eligible low bidder; otherwise, auction result remains.

postponed start of later activities on the chain, causing extension of the scheduled completion date.

Project risks can come from multiple sources such as input delays, mal-functioning equipments, bad progress plan and execution, failure in coordination between prime contractor, subcontractors and suppliers, as well as some idiosyncratic shocks that are beyond contractors' control (weather, local events, earthquakes, and etc.). Roughly speaking, contractors can 'get away' with factors that they don't have control over, and waived of the damages and disruptions of project schedule. But there is still plenty room for things to go wrong on their part which is not compensable.

As project process, the contractor usually gets paid monthly. In the monthly payment vouchers, the Caltran engineers keep records of how the projects proceed. They do so by counting weather days, the total work days and its break down to actual work days, contract change-order days and other days. *Weather days* are "Days on which the Contractor is prevented by inclement weather or conditions resulting immediately therefrom adverse to the current controlling operation or operations, as determined by the Engineer, from proceeding with at least 75 percent of the normal labor and equipment force engaged on that operation or operations for at least 60 percent of the total daily time being currently spent on the controlling operation or operations". Although contractors will not be charged for a working days when above conditions for a weather day is met, they can choose to work on the portion of the day when the weather becomes suitable for construction[4]. *Contract change order days* are generally working days when the contractor performs tasks by the change orders that add or deduct work items from the original plan. Normally these days are not counted toward project deadline and the extra work performed is usually

[4]Refer to "State of California Department of Transportation Construction Standard Specifications May 2006" for more details and explanations.

compensable. It seems that Caltran has a broad definition of *'Other days'* that are roughly days they grant the contractor as time extension for various reasons. 'Other days' are counted as working days, too[5].

3 Theory

3.1 Model Set-up

Let risk-neutral bidders be indexed by i, and let contracts be indexed by j.

The government is the buyer, whose preference of the project j is specified as: $U(q_j, P_j; C_{Uj}) = -C_{Uj}q_j - P_j$, where q_j is a quality measure, herein the number of days to complete the project, and P_j is the price bid for the project. C_{Uj} is the constant and contract-specific per-day externality in dollars. The functional format of governments preference is self-explanatory: completing the project j by one more day costs society welfare loss of C_{Uj}.

With time incentives, it is very reasonable to argue that bidders cost functions should have two parameters: one that controls the traditional material cost and the other governs the acceleration cost (how costly to accelerate) [6].The cost structure of bidder i for project j is a function of time:

$$C_{ij}(q_{ij}; q_j^e, \alpha_{ij}, \beta_{ij}) = \alpha_{ij} + e^{\beta_{ij}(q_j^e - q_{ij})}, q_{ij} \in [q_{ij}^{cp}, q_j^e] \tag{1}$$

where the bidder type parameters α_{ij} (one that controls the material costs or fixed

[5]Caltran terminated the use of 'Other days' starting in 2012 by demanding all time extensions should go through contract change orders

[6]Asker and Cantillon (2010) has a linear, separate and additive cost curve in quality, where fixed cost is a lump sum and quality comes at a constant marginal cost. Lewis and Bajari (2011a) also has a separate additive cost structures with a log-linear specification of marginal costs of acceleration, assuming all bidders' costs have the same elasticity with respect to acceleration. In this paper I follow their lead and take the separate and additive functional form.

costs), β_{ij} (one that controls the acceleration costs) are jointly distributed following some joint distribution function $G(\alpha, \beta)$ on the support $[\underline{\alpha}, \bar{\alpha}]$ x $[\underline{\beta}, \bar{\beta}]$. The first and second derivatives of cost with respect to q are: $C_q < 0$, $C_{qq} > 0$, that is, by having a negative exponential type of cost function, I assume not only costly but increasingly costly acceleration.

q_j^e is engineer-estimated days for project j, which, according to both Caltran and industry practitioners, is a generous measure of the length of production. In fact, Caltran clearly states in the advertisement that no time bids should go beyond the engineer-estimated days. A comparison of A+B and traditional contracts of similar work type and scale indicates that the engineer estimates are about the same. Thus, the engineer-estimated days serves as a good approximation of the amount of time bidders would finish the project had it been procured the traditional way. q_{ij}^{cp} is the 'crash-point' of a contractor i performing project j: number of days under which it is infinitely costly or impossible for this contractor to finish the job. Thus the cost function is convex, decreasing, continuous within the region defined by the interval $[q_{ij}^{cp}, q_j^e]$.

Let indexes be dropped from here on and we have:

$$C(q; q^e, \alpha, \beta) = \alpha + e^{\beta(q^e - q)},\ q \in [q^{cp}, q^e] \text{ , and}$$

$$\text{Fixed cost (or material cost)} = \alpha + 1, \text{ and}$$

$$\text{Acceleration Cost} = e^{\beta(q^e - q)}, \text{ and}$$

$$\text{Marginal cost} = -\beta e^{\beta(q^e - q)}$$

The position of one bidders cost curve is determined by the contract and bidder characteristics, both observed and unobserved, as well as the firms random draw of parameter α: firms that take bigger and more complex projects have cost curves farther out in the cost-day space; everything else the same, a bidder is a weaker competitor/expensive contractor if her draw of α is greater and the bidder is stronger(less costly) if her draw of α is lower. β determines the convexity (or specialization) of bidders cost functions: with α being constant, greater β means it is more expensive for this bidder to accelerate, or, her cost curve is steeper in the cost-day space.

Now I introduce 3 more time quantity variables that are of crucial importance: q_a, q_b, and q_c. Because of unforeseen productivity shocks that take place after bidding, the actual days of delivery should be a stochastic outcome instead of that of the contractor's choosing. Although contractors can plausibly make some arrangements and adjustments, once a series of shocks happen throughout the construction phase, the course of the construction would go beyond the contractor's complete control, leading to a realized time of delivery, q_a. And this realized quantity determines the realized cost at the end of production. The best an experienced contractor can do is guess the expected value of q_a correctly at q_c, the target of completion time. That is, the bidder chooses certain amount of equipment and labor at the beginning of the project, with a goal of days to finish the job—q_c. As the construction proceeds and nature does its work, the bidder finally gets a realization of the radom variable q_a, and in the long run the realizations should center at q_c. In terms of bidding, the contractor proposes a time of q_b in the score she submits, and this quantity may or may not be identical with the target time or actual time. In fact, the bidder optimizes her expected payoff by choosing simultaneously q_b and q_c: choose a q_b to compete for the job and choose a scale and intensity of work (q_c) to perform the job.

Although the explicit per-day penalty of being late is C_{Uj}, the bidder-contract specific true penalty C_{Dij} might differ for several reasons. First, true penalties can be far more severe if bidders value reputation and relation/future business with Caltran. Second, C_{Dij} might even be lower than C_{Uj} if Caltran does not fully enforce the penalty. Last, highway projects sometimes take multiple years to finish and the penalties usually do not be exercised until the end of the project, and this renders being late less penalizing once the time value of money is taken into account[7].

Last, let the distribution function of the random variable q_a be F (with its associated pdf f), centered at q_c with variance σ^2, over the range of $[q^{cp}, q^e]$.

3.2 The Bidder's Optimization Problem

A risk-neutral representative bidder would like to choose two things, a price P and q_c, to maximize her profit once she has won the auction with a score $\bar{S}$ to fulfill:

$$Max\Pi_{P,q_c} = P - E_{q_a}[C(q_a; q^e, \alpha, \beta)] - E_{q_a}[D(q_a, q_b, C_D)] \tag{2}$$

$$\text{subject to } \bar{S} = P + C_U q_b,\ q^{cp} \leq q_c \leq q^e, \text{ and } q^{cp} \leq q_b \leq q^e$$

where $D(q_a, q_b, C_D)$ is the amount of possible disincentive payments from the bidder to Caltran if work is late. Particularly,

$$D(q_c, q_b, C_U) = \begin{cases} (q_c - q_b)C_U, & \text{if } q_c > q_b \\ 0, & \text{otherwise} \end{cases}$$

Substituting the scoring rule, we have:

$$\begin{aligned} Max\Pi_{q_b,q_c} &= \bar{S} - C_U q_b - E_{q_a}[C(q_a; q^e, \alpha, \beta)] - E_{q_a}[D(q_a, q_b, C_D)] & (3) \\ &= \bar{S} - C_U q_b - \int_{q^{cp}}^{q^e} (\alpha + e^{\beta(q^e - t)}) f(t; q_c) \mathrm{d}t \\ &- \int_{q_b}^{q^e} C_D(t - q_b) f(t; q_c) \mathrm{d}t & (4) \end{aligned}$$

$$\text{subject to } q^{cp} \leq q_c \leq q^e, \text{ and } q^{cp} \leq q_b \leq q^e$$

[7]There is an acknowledgement in the industry that bidders might find it optimal to skew bids more on items that can finish earlier (thus also get paid earlier) than items that finish later. This practice is called 'front loading' and might be plausibly due to the time value of money and firms' need for cash flows.

That is, the bidder chooses the target construction time and days bid to minimize the combined externality, expected private construction cost and the expected disincentive payments. Clearly, there are two kinds of trade-offs faced by the bidder: choosing a target construction too big (q_c large) can help save on costs, but might as well increase the risk of going late and paying penalties; bidding too aggressively (q_b small) means a certain higher price offer while maintaining the same score, but higher risk of running late. Thus, the bidder must balance the trade-offs to achieve optimality and this is admittedly a delicate matter.

Although giving intuitive and qualitative predictions, the model above does not readily lead to mathematical and econometrical meanings without any assumptions on the distributions of construction time. Normality is plausibly a good assumption without much loss of generality. To be more specific, let us assume that the distribution $f(q_a; q_c)$ is the pdf of a truncated normal distribution on $[q^{cp}, q^e]$.
Then the first-order conditions are[8]:

$$C_U(1 + \frac{C_D}{C_U} f(q_b^*; q_c^*)(q_b^* - q_c^*))/e^{\frac{1}{2}\sigma^2\beta^2} = \beta e^{\beta(q^e - q_c^*)} \tag{5}$$

$$\frac{C_U}{C_D} = 1 - F(q_b^*; q_c^*) \tag{6}$$

Equations (5) and (6) jointly characterizes the bidder's (with type β) optimal choices on q_b and q_c, given the form of distribution, and C_U, C_D. Equation (5) can be viewed as the tangency of the expected penalty $C_U(1 + \frac{C_D}{C_U} f(q_b^*; q_c^*)(q_b^* - q_c^*))/e^{\frac{1}{2}\sigma^2\beta^2}$ and the (absolute value of the) slope of the cost curve at the optimal target days q_c^*. In (6), the relative magnitudes of C_U and C_D along with the distribution of uncertainty determine the differences in q_b^* and q_c^*. The following is a list of three possible relations between q_b^* and q_c^*.

[8]Detailed proof is given in Appendix

Case 1: If $C_D > 2C_U$, then $q_b^* > q_c^*$. The bidder bids more days than the target construction time to leave some contingency time in light of large amount of penalties. Larger the C_D, more conservative the bid.

Case 2: If $C_D = 2C_U$, then $q_b^* = q_c^*$. In this special case, the bidder's days bid coincide with her target time, and the bidding looks like one where there is no uncertainty.

Case 3: If $0 < C_D < 2C_U$, then $q_b^* < q_c^*$. If the true penalty C_D is less than $2C_U$, the bidder finds it optimal to bid more aggressive than her target work rate. As C_D decreases, it becomes more likely that the best strategy is bid as little as one can[9], since the possible penalties are not sufficient to compensate the higher price one can bid.

3.3 A Brief Detour: Optimality under Certainty

Before going to more predictions of the model, it pays to first look at how a bidder bidding for a project with certainty would strategize. With certainty, Equation (2) becomes:

$$Max\Pi_{P,q_c} = P - C(q_c; q^e, \alpha, \beta) - D(q_c, q_b, C_D) \tag{7}$$

$$\text{subject to } \bar{S} = P + C_U q_b,\ q^{cp} \leq q_c \leq q^e, \text{ and } q^{cp} \leq q_b \leq q^e$$

With substitution of the scoring rule, we have:

$$Max\Pi_{q_b,q_c} = \bar{S} - C_U q_b - C(q_c; q^e, \alpha, \beta) - D(q_c, q_b, C_D) \tag{8}$$

[9] Idealy, the bidder would push this strategy to the extreme, that is, bid just 1 day and finish with the target of q_c and pay possible penalties. But in reality, such bids are considered irregular and even non-responsive, thus tend to get rejected by Caltran. Thus, the lowest she can bid is the 'crash point' q^{cp}.

subject to $q^{cp} \leq q_c \leq q^e$, and $q^{cp} \leq q_b \leq q^e$

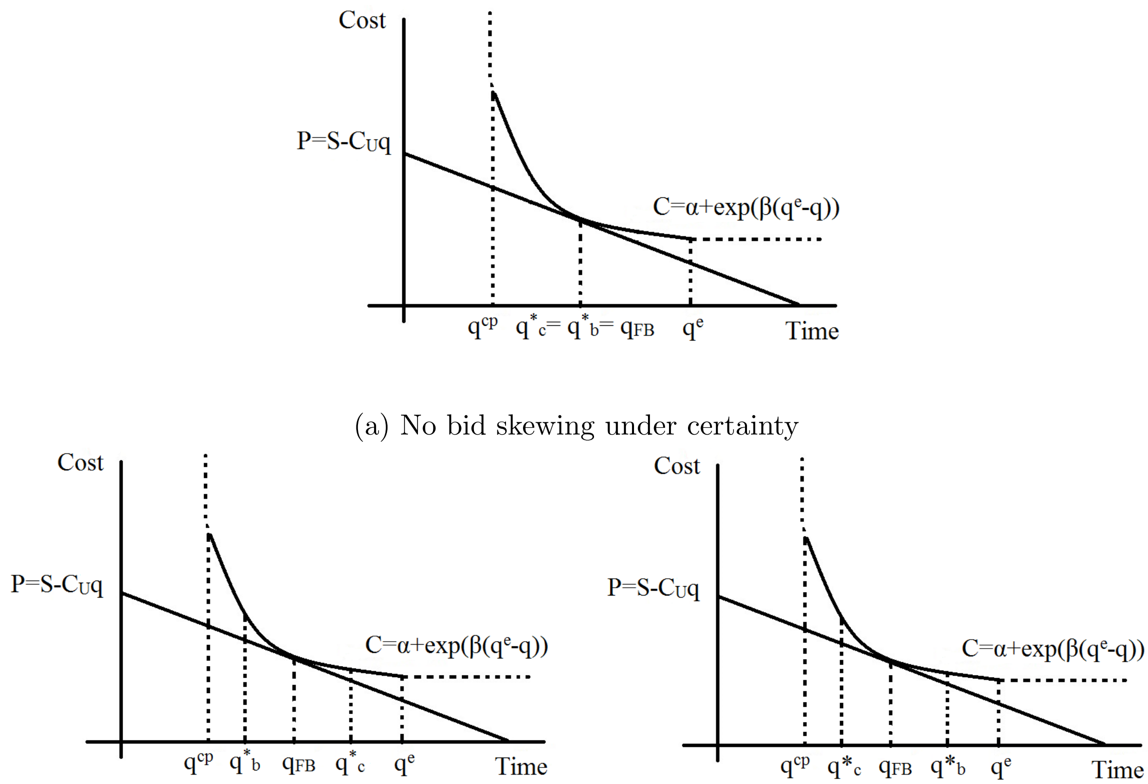
We can take the following approach to come to the bidder's best strategy. Let the choice of q_c be fixed for now at an arbitrary level and (thus the cost of production is also fixed) and let $C_D \geq C_U$. Then the bidder would choose q_b to be equal to q_c, for the following reasons: 1. There is no early-completion reward, so the bidder does not bid more than q_c. That is, when q_b happens to be greater than q_c, decreasing q_b is strictly dominant since it leads to increase in price without increase in penalty. 2. When q_b happens to be less than q_c, increasing q_b by 1 unit means a decrease in penalty by C_D and at the same time a decrease in price by C_U. Thus pushing q_b up toward q_c is strictly dominant when $C_D > C_U$ and weakly dominant when $C_D = C_U$. Hence, there will be no dichotomy of q_b and q_c under certainty with $C_D \geq C_U$: the bidder would finish exactly on the date she bids in the score[10]. In the case of $C_D < C_U$, however, bidders would push down q_b as much as possible by similar reasoning and bid skewing takes place in this case.

In all three cases, however, it should be clear that choice of q_c is determinted by the tangency of the cost function and the scoring rule. Matching the negative marginal cost of the bidder with the user cost C_U gives the following first-order condition:

$$C_U = \beta e^{\beta(q^e - q_c^*)} \tag{9}$$

The nature of A+B auctions fits into the broader class of scoring auctions. Theories developed in this field demonstrate that bidders bid according to their psuedotypes (Che(1993), Asker and Cantillon(2008)). Specifically in A+B procurement

[10]In the special case where $C_D = C_U$, the model does not rule out cases where q_b is not equal to q_c. In fact, it is perfectly fine for the bid to 'travel along' the iso-score line. One realistic argument against differences between q_c and q_b, however, is that bidders don't like to build a reputation of not being able to fulfill the bid. In other words, working on time and fulfilling the contract as bid is considered at least a weakly-dominant strategy.



(a) No bid skewing under certainty

(b) Aggressive bidding under uncertainty: $q_b^* < q_c^*$

(c) Conservative bidding under uncertainty: $q_c^* < q_b^*$

Figure 1: Bid skewing under certainty and uncertainty

This figure shows the main difference in equilibrium bidding behaviors of a model of construction certainty, and a model of construction risk. (a) shows that if no uncertainty, bidders' equilibrium choices of q_b and q_c will be the same and coincide with q_{FB} determined by the tangency. There would be no bid skewing. (b) and (c) give two cases where bid skewing exists in a model of production uncertainty. In particular, bidders would optimally choose q_b and q_c that are almost surely different from each other (with only exception of $q_b = q_c$ when $C_D = 2C_U$). Moreover, either q_b or q_c overlaps with q_{FB} only by 'luck', suggesting that the auction mechanism might cause inefficiency. Note that (b) and (c) are only two representative cases out of 6 in terms of their relative locations with q_{FB}. They are suppressed from the figure because of limited space.

auction setting, one's pseudotype is the social cost of performing the project by this bidder—the combination of private construction cost, expected incentive/disincentive payments, and the public cost or externality. In a scoring auction, the bidder's optimal choice of quality (herein the number of days to complete) is chosen separately from the optimal choice of score. And one's pseudotype is a sufficient statistic at deriving equilibrium bidding behaviors: the bidder with the lowest psuedotype, or psuedocost, wins the contract in the same way that a buyer with the highest valuation in a standard first-price sealed-bid auction wins the auction with the highest bid. Since bidders always equate the weight on days in the scoring rule with their marginal costs of acceleration to obtain the optimal days bid, *ex-post* efficiency is guaranteed by the tangency (of the iso-score line and own cost curve) and *ex-ante* efficiency is guaranteed by the competitive nature of auction (Lewis and Bajari (2011a)). However, this conclusion is crucially relying on the latent assumption of certainty, and once uncertainty is introduced, the efficiency of A+B breaks down.

3.4 Optimal Choice of q_b, q_c, and Equilibrium Bidding Strategy

A simple comparison of (9) with (5) shows that with uncertainty built into the model, bidder's optimal target construction time is such that the cost curve takes the slope of the Left Hand Side of Equation (5) (in absolute value). Instead of C_U, which is the case in the certainty model, this slope has an extra term $(1 + \frac{C_D}{C_U} f(q_b^*; q_c^*)(q_b^* - q_c^*))/e^{\frac{1}{2}\sigma^2\beta^2}$ which depends on the values of C_D, C_U, σ^2, β. Since σ^2 and β are both positive, the denominator $e^{\frac{1}{2}\sigma^2\beta^2}$ is greater than 1; also, the term $\frac{C_D}{C_U} f(q_b^*; q_c^*)(q_b^* - q_c^*)$ is positive for any q_b not equal to q_c, making the numerator greater than 1. Thus, the coefficient $(1 + \frac{C_D}{C_U} f(q_b^*; q_c^*)(q_b^* - q_c^*))/e^{\frac{1}{2}\sigma^2\beta^2}$ can be greater than, equal to, or less than 1, depending on the relevant parameter values, meaning that the optimal target time under uncertainty can be greater than, equal to, or less than its counterpart in a world of certainty. Given this, whether bidders choose a tighter schedule under construction uncertainty or a looser one is an empirical matter.

The bidder's optimal choice of q_c and q_b are defined implicitly by both (5) and (6):

$$q_c^* = g_1(C_U, C_D, \beta, \sigma^2, q^e) \tag{10}$$

$$q_b^* = g_2(C_U, C_D, \beta, \sigma^2, q^e) \tag{11}$$

Clearly, the optimal time quantities don't depend on the bidder's draw on α—material cost or fixed cost does not affect things on the margin. If one takes Taylor expansion of (6) to the second order, one gets:

$$q_b^* - q_c^* = (\frac{1}{2} - \frac{C_U}{C_D})\sqrt{2\pi}\sigma \tag{12}$$

That is, the magnitude of bid skewing is determined linearly in the ratio of C_U and C_D, and also linearly in the amount of project risk σ.

Since I introduce uncertainty as the main feature of the model, the types in this paper are all in the sense of expectation. Let $C_0(C_U, C_D, \alpha, \beta, \sigma^2, q^e) = C_U q_b^* + C(q_c^*; C_U, C_D, \alpha, \beta, \sigma^2, q^e)$ for the bidder type (α, β), where C_0 is indeed the bidder (α, β)'s pseudotype or pseudocost (combination of expected public externality of $C_U q_b^*$ and private minimized expected cost of production). This is an analog of valuation from the standard first-price sealed-bid auction paradigm.

Having figured out the optimal choice of time quantities, what is left for the bidder to do is choose a price to complete the score. I will follow the theoretical literature on scoring auction to briefly illustrate the process. Now consider the following change of variables:

$$v = C_0(C_U, C_D, \alpha, \beta, \sigma^2, q^e)$$
$$H(v) = G_{\alpha,\beta}(V^{-1}(v))$$
$$b \equiv score = C_U q_b^* + P$$

Then the problem now can be interpreted as one where a firm having cost potential v with cumulative distribution $H(\cdot)$, proposes to meet the level of score b. The objective function for the bidder is then:

$$
\begin{aligned}
& E\Pi(q_c^*, q_b^*, P|C_U, C_D, \alpha, \beta, \sigma^2, q_e) \\
& = [P - C(q_c^*; C_U, C_D, \alpha, \beta, \sigma^2, q_e)] Pr\{win|C_U q_b^* + P\} \\
& = [b - v]\{1 - H(b^{-1}(b))\}^{N-1}
\end{aligned}
$$

The equilibrium price can be obtained by simple reference to the usual result of first-price sealed-bid auction paradigm and change of variables.

3.5 Inefficiency of A+B

Recall in Section 3.2 that if there is no construction risk, the tangency of social usercost and bidder's cost function gives the first-best outcome (both *ex-ante* and *ex-post* efficient) of A+B auctions, where private interest is willingly aligned with social interest. And this welfare outcome holds as long as $C_D \geq C_U$. Even with uncertainty introduced into the model, the first-best point is still the same tangency as long as expectations are correct in equilibrium[11]. The failure to arrive at the first best under uncertainty, though, is due to the fact that the possible C_D becomes relevant in private optimization and does affect things on the margin, as well as the fact that the scoring rule does not fully address the whole set of incentives bidders face.

To be specific, the types demanded by first best are $T_{i0} = C_U q_{FBi}^* + C(q_{FBi}^*)$, where

[11] Think about a scenario where the government has perfect information on private construction cost and the knowledge of uncertainty, then the benevolent government can and will push the society onto the tangency point if it is able to command the private firm to do so(or if it owns the firm)

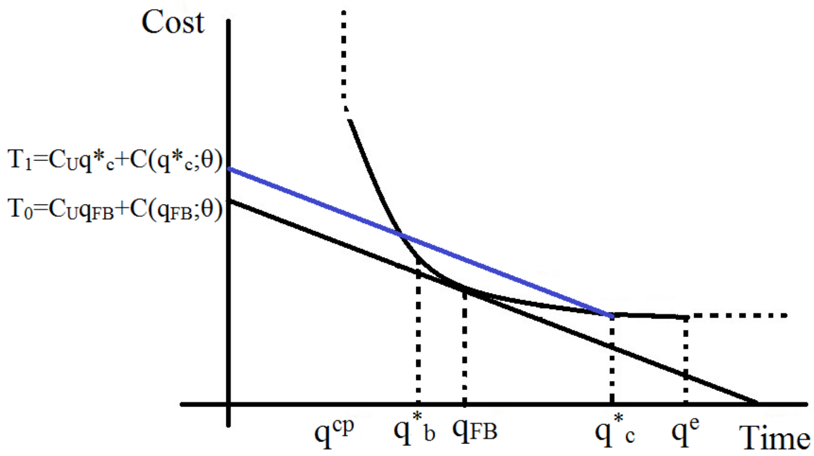
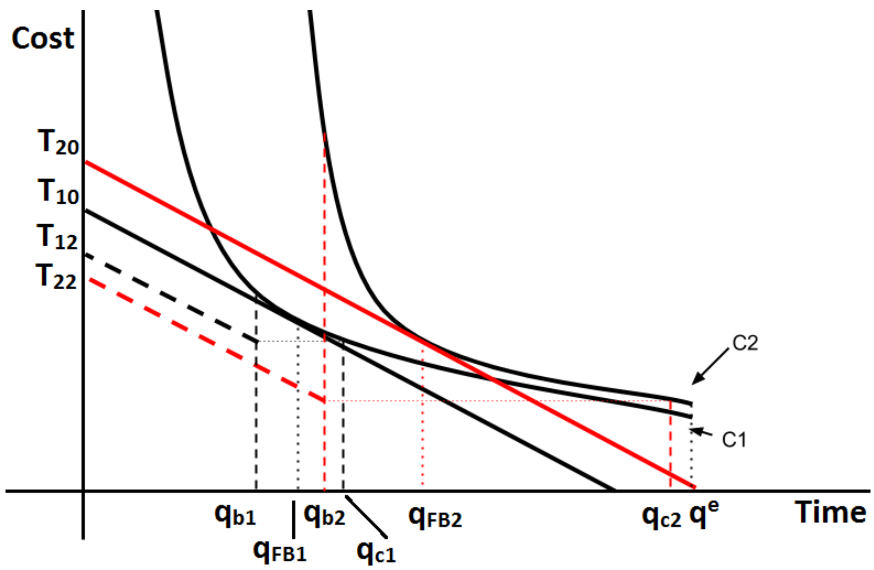


Figure 2: *Ex-post* inefficiency with uncertainty

q^*_{FBi} is the first-best quantity at the tangency, while the private parties actually act on and deliver the types $T_{i1} = C_U q^*_{ci} + C(q^*_{ci})$. Figure 2 shows that as long as cost is convex with respect to time, choices of q_c that are different than q_{FB} will lead to *ex-post* inefficiency, regardless of who wins the auction[12].

The bidders, delivering T_1, bid with the types $T_{i2} = C_U q^*_{bi} + C(q^*_{ci})$. Thus it is possible that the rank of bids by T_2 might fail to align with the rank by T_0, causing a failure to achieve *ex-ante* efficiency, as depicted by Figure 3. In the case described in Figure 3, the second bidder (in terms of social welfare, or T_0) with bigger α and β (hence overall more costly) becomes the winner by bidding very low and targeting late. And the overall more efficient bidder, 1, chooses q_b and q_c fairly close to q_{FB} but end up losing the auction. This is an outcome caused by the auction mechanism with construction uncertainty that possibly rewards slower and more expensive bidders through their equilibrium bidding behaviors. One thing to note is that Figure 3 only illustrates one possible combination of underlying structural parameters that result

[12]For illustration purpose and limitation of space, Figure2 only lists one of the possible cases of relations between q_b and q_c where $q_c \neq q_{FB}$. It should be clear that T_1 is above T_0 as long as the convexity assumption of the cost remains to hold.



$$T_{10} = C_U * q_{FB1} + C_1(q_{FB1}; \theta_1)$$
$$T_{12} = C_U * q_{b1} + C_1(q_{c1}; \theta_1)$$
$$T_{20} = C_U * q_{FB2} + C_2(q_{FB2}; \theta_2)$$
$$T_{22} = C_U * q_{b2} + C_2(q_{c2}; \theta_2)$$

Figure 3: *Ex-ante* inefficiency with uncertainty

in the displacement shown here, if one observes that the displacement is caused by either winner's q_b much higher, or her q_c is much lower, or both, compared to the choice variables of the social-welfare-maximizing bidder.

One might feel that the first-best outcome is too much to ask for, since the theory demonstrates that inefficiency always follows due to winners' choices of production rates that differ with the tangency. Then what seems to be a more appropriate question to ask is: can the auction mechanism assign the project to the bidder with the lowest social cost of production (i.e. T_1)? That is, what we are interested in is whether awarding the contract on the basis of T_1 selects the bidder who maximizes welfare subject to the constraint that they produce at a sub-optimal rate (q_c)—a second best outcome. Consider two bidders, 1 and 2, with $T_{11} = C_U q^*_{c1} + C_1(q^*_{c1}; \theta_1)$ and $T_{21} = C_U q^*_{c2} + C_2(q^*_{c2}; \theta_2)$ and say Bidder 1 is the low bidder in T_1. Referring to their types in bidding $T_{12} = C_U q^*_{b1} + C_1(q^*_{c1}; \theta_1)$ and $T_{22} = C_U q^*_{b2} + C_2(q^*_{c2}; \theta_2)$ we see that the model does not rule out the possibility that Bidder 2 wins the auction with a sufficiently low q_b.

4 Descriptive Evidence

4.1 Data

The dataset of this paper was constructed mainly with data publicly available from Caltran website, along with several other sources. A total of 225 A+B contracts with 1341 bids were observed in the period of 2003-2013. The variables of the dataset are grouped into four parts: contract-level key variables, contract characteristics, bidder characteristics, and *ex-post* performance variables and they are summarized in Table 2 and Table 3. Although this data set is a panel, I only make use of the cross-sectional variations for the estimation.

An average project is estimated by Caltran engineers at about $26 million and average A parts is about $24 million. These highway contracts are comparably large with engineer estimates of days at around 352 days. Bidders' days bid are on average 212 days, or approximately 61% of engineer days estimates. On average, 6.9 bidders participate in an A+B auction, with the minimum number of bidders of 2 and maximum of 14[13]. Usercosts vary across projects, from as low as $1600 to almost $100,000, with the average of $14,769. The traffic volume can be very different for different project sites. An average bidder is a bit over 100 miles distant to the project it bids on. About 77% of the projects get full or partial federal funding. Furthermore, the majority of the projects belong to four categories: widen&realign, pavement, road rehabilitation, and bridge work.

[13]There are a couple of auctions ending up with only one bidder participating, but they were taken out from my data set for estimation purpose.

Also, I collect information on contract-level characteristics that can account for inter-contract differences in job complexities including: number of bid items, disadvantaged business goals, number of proposals, number of addendums, pages of contract advertisements, and amounts of design details[14]. And the last block of variables prescribes to bidders. 97% of the bids are submitted by California-based firms, and 5% by a joint venture (an entity that consists two or more different firms bidding as one bidder). I follow the literature practice and regard a firm as 'Fringe firm' which bids in no more than 4 auctions in the entire sample period. Out of 170 different entities that participated in these 225 auctions, 105 of them are fringe firms, although they only account for 12% of all bids. Furthermore, I also made dummy variables on the largest 4 firms in terms of number of auctions they've participated in: Granite, Diablo, RGW and O.C. Jones, and these firms together account for about one fifth of all bids. Also included in the data set is participation experience, which is the number of A+B auctions that a bidder has bid on in the sample period (average is 16.3 times) and winning experience, which is the number of A+B auctions that a bidder has won in the sample period (average is 2.8 times).

The next part of the data consists *ex-post* performance variables collected from payment vouchers from 'Major Construction Payment and Information' of Caltran's Accounting Division. In the monthly payment vouchers, the Caltran engineers keep

[14]Bid items are generally specific tasks that bidders bid on and serve as a proxy of the project complexity. And this count ranges from 11 to 345 with an average at 120. Disadvantaged business goals is in percentage terms, a lower bound on the amount of work that has to be performed by disadvantaged business, and simply capturing Caltran's preference to disadvantaged business to take part in the construction. Number of proposals indicates how many firms took the efforts to get the proposals and showed interest to participate in the bidding and it also gives some idea on the competitiveness of the project besides 'number of bidders'. Number of addendums to the original advertised contract special provision accounts for the changes and modifications that take place after advertisement and before bidding. Most of the projects only need a couple of addendums to make things complete, although a few contracts call for 10 or more addendums to supplement. I also estimated the content volume of each contract by looking at number of pages and counting how many subsections in special provisions that are dedicated to construction details.

records of how the projects proceed. They do so by counting weather days as well as the total work days and its break down to actual work days, contract change-order days and other days. They are summarized in Table 3.

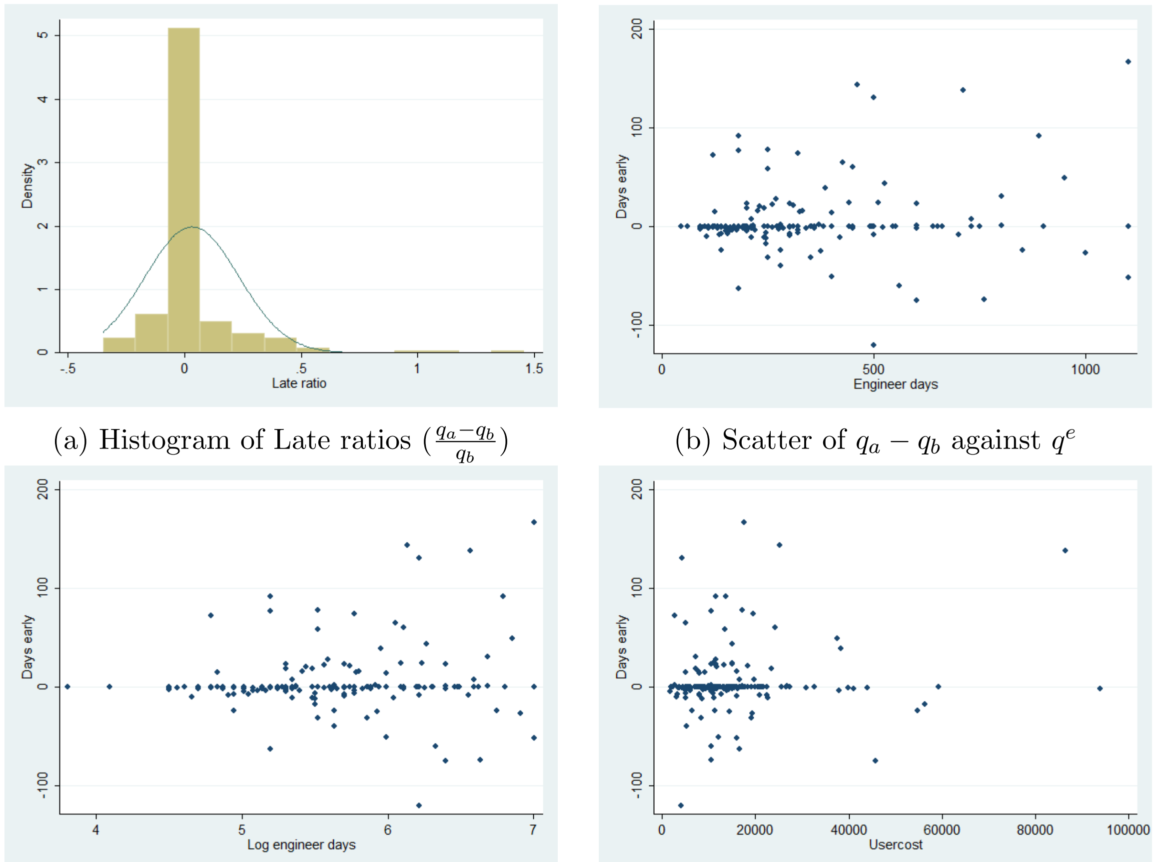
Analysis of participation patterns of A+B auctions calls for data on both A+B auctions and similar traditional auctions(the ones that could've become A+B auctions), which inevitably takes huge amount of time and efforts that the author of this paper alone cannot afford. Participation, however, should not be a major concern primarily due to the following argument: projects of Caltran become available only when a need is detected, which happens randomly at least to the bidder. Another way to put it is—instead of picking one project out of a menu of projects lying in front of the bidder, any one bidder faces a queue of upcoming projects that is chosen by nature. In this sense, the nature of the industry greatly reduce bidders behaviors of project selection and participation[15].

4.2 Graphical Analysis

Out of these 225 projects, 187 have been completed by Sep 30th, 2014. 78 contracts finished exactly on time, 69 contracts finished early, and 40 projects finished late. Out of the 40 late projects, 17 projects were charged penalties and 12 of them got penalties removed in the end. Figure 4 Graph (a) shows a histogram of the variable Lateratio, which is the percentage of days late over days bid. Negative numbers mean early completion, 0 on-time completion and positive numbers late delivery. On average, projects get delivered 3% late according to data recorded by resident engineers.

If there was no risk in construction, then we would expect Graph (a) to be one

[15] Also, Lewis and Bajari (2011) performs a reduced form logit model of bidder participation and their conclusion is that" There is little evidence that A+B contracts attract more or less participation relative to the control group...matching is essentially based on size and distance, rather than A+B status".



(a) Histogram of Late ratios ($\frac{q_a - q_b}{q_b}$)

(b) Scatter of $q_a - q_b$ against q^e

(c) Scatter of $q_a - q_b$ against $log(q^e)$

(d) Scatter of $q_a - q_b$ against C_U

Figure 4: Evidence of model predictions

where there is only one mass point at 0, meaning that contractors would all just finish on time. And this is because if certainty is true, there is no incentive for the bidder to go either early or late when she can perfectly avoid both after the contract is awarded. Fact is, instead, we observe sizable fluctuations of final construction time, which is suggestive of the shocks that took place during the construction process causing the deviations.

Also, this may be suggesting that there exists a difference between bid days and target days systematically since apparently the risk of construction 'favors' 'late' significantly over 'early'— most of the early projects are only early by a few days whereas the late ones tend to be substantially late and causing real damages. With the initial look at the data, one finds that this may be consistent with bidders' aggressive bidding behaviors, that is, bidding fewer days than what is actually planned, compared with other possibilities. Moreover, this might be made possible by the likely low rate of enforcement on Caltran's end, and we will come back to this point later.

Recall from Section 3 Equation (12) that the difference between the equilibrium choices of q_b and q_c is a function of C_U, C_D and σ, thus larger the uncertainty, larger the difference between the two quantity choices. It is also plausible to treat scales of projects as a proxy of project risk since uncertainty tends to scale with project duration, complexity, etc. Hence if the theory is correct, we should expect the difference between the realized days, q_a, and days bid, q_b, to scale with engineer days q^e or similar measures of project magnitudes. Remember that we can use q_a in place of q_c in the analysis here because of the assumption that q_a is a realized outcome of q_c. Graph (b) and (c) of Figure 4 show that indeed this is the case (even though the 'fan out' pattern is much more obvious in Graph (c) with log engineer days on the x-axis).

Graph (d) of Figure 4 shows that there is no clear association between usercost and $q_a - q_b$, and this does not contradict with the theory: only the ratio of C_U and C_D affects $q_a - q_b$ and the individual effects of C_U and C_D are not obvious or definitive given that we do not know how C_U affects C_D.

As the theory indicates, the magnitude of C_D and its comparison with C_U identify which case out of 3 the bidders' behaviors fall into: conservative bidding ($q_b > q_c$), honest bidding ($q_b = q_c$), or aggressive bidding ($q_b < q_c$). There are many factors that potentially affect C_D: reputation considerations, time value of money, and enforcement rate of Caltran, etc. Explicitly building these factors into the mechanism analyzed here would go very much beyond the scope of this study. Thus I treat the effect of all these factors as one-dimensional variable C_D and only argue about the direction of the impacts of these factors on C_D.

Weather days, Contract change-order days and Other days are potentially good ways of bidders' adaptation after contract approval and hence actual lower enforcement rate on Caltran's part. Focusing on how bidders adjust their *ex-post* work rate in response to production shocks and using data from Minnesota DOT, Lewis and Bajari (2013) find evidence of adaptation of bidders along dimensions such as "working on days that they are not required to". A look into Caltran's official guidelines and standard specifications of highway projects suggests that this also seems to be the case in California. Contractors, facing high-powered incentives and tight schedules, tend to work positive hours on days (such as weather days) that don't count toward project deadline. And what seems also happening is that project engineer can grant extra days through Contract Change-order days or Other days if they find doing so serves the best interest of the state. Hence the enforcement of A+ B contracts may not be 100% as one would expect.

Table 3 gives readers some idea of possible adaptation and low enforcement rate by the three ratios: weather days/q^e, CCO days/q^e, and Other days/q^e. These ratios are large and take up a significant portion of the total duration of the projects. However large and significant, these statistics are not so convincing if not compared with traditional or A-only projects. Table 1 provides a part of Table 1 from Lewis and Bajari (2011) where the counts of different days are compared between A+B and A-only projects over 2003-2008. Although weather days and other days are not significantly greater than those of A-only projects, working days for A+B contracts are significantly lower than that of A-only contracts, meaning a drastically higher ratio of weather days and other days to working days. And this is evidence favoring bidders' adaptation along this margin and Caltran's low enforcement rate on A+B:

bidders work on weather days (which do not count toward deadline) proportionately more in A+B and Caltran is linient and grant porportionatly more Weather days and Other days for A+B projects which alleviates the schedule pressure on bidders to some extent.

Taken together, evidence given in this section suggests that the broad picture of A+B bidding that emerges here is one where bidders find it optimal to target late (big q_c) and bid early (small q_b). Nonetheless, this is only an initial look at the data rather than solid arguments. Formal structural estimation needs to be performed to truly lift the veil of A+B bidding.

4.3 Reduced-form Evidence on Bidding

To know a little bit more about A+B auction outcomes than the summary statistics, I performed 3 reduced-form OLS regressions: log price, days bid, and days late ($q_a - q_b$) on various contract and bidder covariates. And they are:

$$
\begin{aligned}
& logprice_{ij} = \pi_{p0} + \pi_{p1} LogC_{Uj} + \pi_{p2} Numberofbidders_j + \pi_{p3} Logengest_j \\
& + \pi_{p4} Logtraffic_j + \pi_{p5} Distance_{ij} + \pi_{p6} Distance_{ij}^2 + \pi_{p7} Federal_j \\
& + \pi_{p8} Biditems_j + \pi_{p9} Dbgoal_j + \pi_{p10} Addendums_j + \pi_{p11} Pages_j \\
& + \pi_{p12} Designdetails_j + \pi_{p13} Instate_i + \pi_{p14} Fringefirm_i + \pi_{p15} Granite_i \\
& + \pi_{p16} Diablo_i + \pi_{p17} RGW_i + \pi_{p18} OCJones_i + \pi_{p19} JV_i + \pi_{p20} ParExp_{ij} \\
& + \pi_{p21} WinExp_{ij} + \pi_{p22} Win.Par_{ij} + IndustryFE_j + YearFE_j \\
& + DistrictFE_j + error_{ij}
\end{aligned}
$$

$$q_{bij} = \pi_{b0} + \pi_{b1} LogC_{Uj} + \pi_{b2} Numberofbidders_j + \pi_{b3} Logengest_j + \pi_{b4} Logtraffic_j$$

$$+ \pi_{b5} Distance_{ij} + \pi_{b6} Distance^2_{ij} + \pi_{b7} Federal_j + \pi_{b8} Biditems_j + \pi_{b9} Dbgoal_j$$

$$+ \pi_{b10} Addendums_j + \pi_{b11} Pages_j + \pi_{b12} Designdetails_j + \pi_{b13} Instate_i$$

$$+ \pi_{b14} Fringefirm_i + \pi_{b15} Granite_i + \pi_{b16} Diablo_i + \pi_{b17} RGW_i + \pi_{b18} OCJones_i$$

$$+ \pi_{b19} JV_i + \pi_{b20} ParExp_{ij} + \pi_{b21} WinExp_{ij} + \pi_{b22} Win.Par_{ij} + IndustryFE_j$$

$$+ YearFE_j + DistrictFE_j + error_{ij}$$

$$DaysLate_{ij} = \pi_{e0} + \pi_{e1} LogC_{Uj} + \pi_{e2} Numberofbidders_j + \pi_{e3} Logengest_j$$

$$+ \pi_{e4} Logtraffic_j + \pi_{e5} Distance_{ij} + \pi_{e6} Distance^2_{ij} + \pi_{e7} Federal_j + \pi_{e8} Biditems_j$$

$$+ \pi_{e9} Dbgoal_j + \pi_{e10} Addendums_j + \pi_{e11} Pages_j + \pi_{e12} Designdetails_j + \pi_{e13} Instate_i$$

$$+ \pi_{e14} Fringefirm_i + \pi_{e15} Granite_i + \pi_{e16} Diablo_i + \pi_{e17} RGW_i + \pi_{e18} OCJones_i$$

$$+ \pi_{e19} JV_i + \pi_{e20} ParExp_{ij} + \pi_{e21} WinExp_{ij} + \pi_{e22} Win.Par_{ij} + IndustryFE_j$$

$$+ YearFE_j + DistrictFE_j + error_{ij}$$

The estimation results are shown in Table 4. All other things held constant, increase in usercost suggests increase in price bids, decrease in days bid and higher propensity of being late. On average one more participant of the auction leads one existing bidder in the same auction to shade its price offer by 2.5% as well as its days bid by 11.87 days, indicating the extent of competition of the auction environment. Number of bidders, however, does not significantly impact the performace of the contract, which may give support to the Independent Private Value (IPV) assumptions of the model. The scales of the projects, measured by logs of engineer estimates, are associated with higher price bids, longer project duration bids and fewer days late. The large literature on highway construction has a consensus that the further a bidder is from the job site, the higher both the base cost and acceleration cost, with higher price bid and days bid. The estimates agree with this. What is also worth mentioning is the group of contract complexity variables having positive association with days bids and price bids, suggesting that more complex jobs lead to longer projects and higher prices presumably caused by higher costs. The group of firm type variables suggests heterogeneity in firms' tradeoffs between base costs and acceleration costs. Moreover, fringe firms tend to finish the projects early compared with bid four firms. And this can be due to the more conservative bidding behaviors of fringe firms: bidding relatively more days helps to avoid being late. The two experience variables and their interaction seem to affect days bid very much although they have a neutral effect on price bids. Nonetheless, no sensible empirical analysis can be done without first figuring out the specifics of the auction mechanism and bidder optimization process. Thus no structural interpretation shall be inferred out of the results shown here.

5 Structural Approach

5.1 Empirical Model from First-Order Conditions

As is seen in Section 3, the cost function of each individual bidder has her own acceleration parameter β in the theoretical model. To facilitate empirical estimation, I take the following variation of the cost function:

$$C_{ij} = \alpha_{ij} + e^{\beta_0(\frac{q_j^e - q_{ij}}{q_j^e})} e^{X_{ij}\theta_\beta + \epsilon_{\beta ij}}, q_{ij} \in [q_{ij}^{cp}, q_j^e] \tag{13}$$

where β_0 substitutes for $\beta_{ij} q_j^e$, and is common to all bidders and all contracts. X_{ij} is a row vector of bidder and contract characteristics and θ_β is a column vector of parameters. $\epsilon_{\beta ij}$ captures bid-specific random errors, and $\epsilon_{\beta ij} \overset{iid}{\sim} N(0, \sigma^2_{\epsilon_\beta})$. $X'_{ij}\theta_\beta + \epsilon_{\beta ij}$ gives the individual component, allowing for variations in acceleration costs across bidders and contracts. β_0 captures the common part of the curvature of the cost function and furthermore, and it takes the economic meaning of elasticity of acceleration since (let the amount of acceleration cost $e^{\beta_0(\frac{q_j^e - q_{ij}}{q_j^e})} e^{X_{ij}\theta_\beta + \epsilon_{\beta ij}}$ be denoted as C_{Aij}):

$$lnC_{Aij} = \beta_0(\frac{q_j^e - q_{ij}}{q_j^e}) + X_{ij}\theta_\beta + \epsilon_{\beta ij} \tag{14}$$

That is, holding all other things constant, for one percentage decrease in construction time, the amount of acceleration cost increases by $\beta_0\%$. Bear in mind the economic meaning of β_0 since substitution of β_0/q_j^e with β is needed because one needs to avoid same variable (hereby q_e) appearing on both sides of an equation. And this point will be clearer as we go on. Note that the new β has no subscripts associated with it, meaning that apart from the effect of q^e, we are again estimating how costly for the bidders to accelerate, on average.

Taking Equilibrium condition (6) into (5), we have:

$$C_{Uj}(1 + \frac{f_{ij}(q_{bij}^*; q_{cij}^*)}{1 - F_{ij}(q_{bij}^*; q_{cij}^*)}(q_{bij}^* - q_{cij}^*)) = e^{\frac{1}{2}\sigma_{ij}^2\beta^2}\beta e^{\beta(q_j^e - q_{cij}^*)} e^{X_{ij}\theta_\beta + \epsilon_{\beta ij}} \tag{15}$$

Note that the unobservable bid-specific true penalty C_{Dij} does not show in Equation (14). To go further, let us make the following identification assumption:

Identification Assumption 1: Assume $q_{bij}^* - q_{cij}^* = \delta_{ij}\sigma_{ij} = (\bar{\delta} + Z_{ij}\gamma + \epsilon_{\delta ij})\sigma_{ij}$, where $\delta_{ij} = \bar{\delta} + Z_{ij}\gamma + \epsilon_{\delta ij}$ captures the bid-specific distance between q_{bij}^* and q_{cij}^* and $\epsilon_{\delta ij} \overset{iid}{\sim} N(0, \sigma_{\epsilon_\delta}^2)$. Specifically, it consists of the common part $\bar{\delta}$ and the individual part $Z_{ij}\gamma$, where Z_{ij} accounts for the individual characteristics that potentially affect C_{Dij}. This specification is motivated by the theory (Equation (12)) where the difference between these q_b and q_c are solely determined by C_{Dij} , C_{Uj} and σ_{ij}. Thus

δ_{ij} should incorporate things that affect C_{Dij} and clearly, this quantity should vary across bidders and auctions. Although bidders know their δ_{ij} given prior information they have, δ_{ij} remains random to the researcher thus $\bar{\delta}$ and γ should be estimated. After some algebra, Equation (15) can be re-written as[16]:

$$q^*_{bij} = -\frac{1}{\beta} lnC_{Uj} + \delta_{ij}\sigma_{ij} + \frac{1}{2}\beta(\sigma_{ij})^2 + q^e_j + \frac{ln(\beta)}{\beta} - \frac{1}{\sqrt{2\pi}\beta}\delta_{ij} + \frac{1}{\beta}X_{ij}\theta_\beta + \frac{1}{\beta}\epsilon_{\beta ij} \tag{16}$$

Identification Assumption 2: $\sigma_{ij} = wq^e_j log(q^e_j) + \epsilon_{\sigma ij}$. There are two reasons for modeling uncertainty this way: first, project scale serves as a natural proxy of project risk/uncertainty; second, once normalized with project scale q^e_j (Thus let $\sigma_{ij}/q^e_j = \sigma^N_{ij}$), the standard deviation still linearly depends on project scale: larger projects tend to be more risky even after normalization. Also, $\epsilon_{\sigma ij} \overset{iid}{\sim} N(0, \sigma^2_{\epsilon_\sigma})$, and $E(\epsilon_{\sigma ij}|q^e_j) = 0, \forall i, \forall j$.

Identification Assumption 3: $\epsilon_{\beta ij} \perp \epsilon_{\delta ij}$, $\epsilon_{\beta ij} \perp \epsilon_{\sigma ij}$, $\epsilon_{\delta ij} \perp \epsilon_{\sigma ij}$, $\forall i, \forall j$.

After substitution and rearranging, (16) becomes the empirical model I try to estimate:

$$\begin{aligned} q^*_{bij} = &-\frac{1}{\beta} lnC_{Uj} + w\delta_{ij}q^e_j log(q^e_j) + \frac{1}{2}\beta w^2(q^e_j log(q^e_j))^2 + q^e_j + \frac{1}{\beta}X_{ij}\theta_\beta \\ &+ \frac{ln(\beta)}{\beta} - \frac{1}{\sqrt{2\pi}\beta}\bar{\delta} - \frac{1}{\sqrt{2\pi}\beta}Z_{ij}\gamma + \frac{1}{2}\beta\epsilon^2_{\sigma ij} + error_{ij} \end{aligned} \tag{17}$$

where $error_{ij}$ is $\epsilon_{\delta ij}wq^e_j ln(q^e_j) + \epsilon_{\delta ij}\epsilon_{\sigma ij} + \bar{\delta}\epsilon_{\sigma ij} + Z_{ij}\gamma\epsilon_{\sigma ij} + \beta wq^e_j log(q^e_j)\epsilon_{\sigma ij} - \frac{1}{\sqrt{2\pi}\beta}\epsilon_{\sigma ij} + \frac{1}{\beta}\epsilon_{\beta ij}$ and has mean zero. The term $\frac{1}{2}\beta\epsilon^2_{\sigma ij}$ ceases to follow a normal distribution and the mean is not zero, but the impact from this term is only on the intercept.

[16]Detailed derivation is provided in Appendix.

Nevertheless, Model (17) suggests that a simple OLS suffices in giving us unbiased estimates of β, w, $\bar{\delta}$, γ and θ_β, although the estimation is subject to heteroskedasticity.

The estimation results are shown in Table 5. For the degree between separation of q_b and q_c, I make use of firm types and variables on experiences and interactions with Caltran to account for the heterogeneity in firms' choices of δ's, as these factors tend to associate with firms' reputation, demand for more cash flows, and expectation of Caltran's enforcement rate on A+B contracts. Four similar models were tested on and estimates across specifications are comparable. Model (1) is the baseline model presuming constant $\bar{\delta}$ without year or district fixed effects; Model (2) is the baseline model including year or district fixed effects; Model (3) includes firm type interactions with $q^e ln(q^e)$; Model (4) includes firm type and experience interactions with $q^e ln(q^e)$.(Industry fixed effects are included in all models. Year and District fixed effects are included in all models except (1).) I go with Model (4) for model interpretations since it is the full-blown version of the estimation.

β is significantly estimated at $1/10.99 = 0.091$, thus β_0 is expected to center on 32 (0.091multiplied by average of engineer days), unveiling the underlying acceleration cost in this industry: speeding up by 1% of the schedule induces a 32% increase on acceleration cost; or, acceleration cost more than triples with a 10% cut on schedule.

The second striking finding in this regression result is that the statistically significant and robust coefficient on $(q^e ln(q^e))^2$, indicating a positive estimate of w, which immediately claims the existence of construction uncertainty. Since the parameter before this term is $\frac{1}{2}\beta w^2$, the value of w gets pinned down at 0.0104. The average of engineer-estimated days being 352.43 and average of the log of this variable 5.68, one obtains the expected standard deviation of 22.09 days on the 352-day project. Or that the expected uncertainty is around 6% of the project scale, once normalized by engineer days. Different project sizes lead to different levels of risk: in this sample of data, the normalized uncertainty σ^N ranges from 3.9% to 7.6%.

Another important finding is the overall aggressive bidding patterns of bidders, as illustrated jointly by the estimates of coefficients on $q^e ln(q^e)$, and its interactions with firm types and experiences. Although not statistically significant, estimated coefficient of $q^e ln(q^e)$ is negative across all specifications and the magnitudes compare. Also, different firm types differ in how they shade q_b from q_c. As opposed to other bidders, fringe firms tend to bid more 'honestly' by choosing days bid closer to construction target time and this is consistent with the story of this paper: fringe firms are small bidders who seldom participate in A+B auctions and hence lack experience both in speedy construction and interactions with Caltran. And these factors probably make fringe firms value reputation and future business with Caltran more, and yet at the same time make them inexperienced in and hence overestimate how Caltran enforces the contracts. To make the above analysis even more credible, the estimated coefficients on interactions of $q^e ln(q^e)$ and participation and winning experiences are both negative, showing again how experience and interactions with Caltran help in aggressive bidding behaviors. Taken together, the δ's center at -4.42, with min of -5.64 and max of -2.75, suggesting that a representative bidder would shade her bid down from the target time by 4.4 times of the standard deviation of production uncertainty. And this finding corresponds to the Case 3 in the theory, suggesting that the true penalties the bidders face should be at least lower than twice of the road user costs.

5.2 Estimating Distributions of Normalized Bids

Following Guerre, Perrign, and Vuong(2000), the structural analysis of auction data recovers the underlying distribution of types by investigating the distribution of observed bids. Relevant to scoring auctions, the underlying distribution of bidders pseudotypes can be identified from observed scores, number of bidders and contract and bidder characteristics. Specifically in A+B setting:

$$v_{ij} = b_{ij} - \frac{1}{(N_j - 1)} \frac{[1 - H(b_{ij})|X_{ij}, N_j]}{h(b_{ij}|X_{ij}, N_j)} \tag{18}$$

where v_{ij} is bidder i's pseudocost, b_{ij} bidder i's score submitted for contract j, N_j the number of bidders that participate in auction j, and X_{ij} the set of contract and bidder characteristics.

If the projects were homogeneous, then simple non-parametric estimations of unconditional cumulative distribution and densities of scores would suffice. Highway procurement projects, to a very large degree, are complex and unique in nature. So the valuations of different projects should be conditioned on project and firm characteristics. If we want to control heterogeneity, nonparametric approach proposed by Guerre, Perrign, and Vuong(2000) would suffer a great deal from the curse of dimensionality. Hence, a two-step psemi-parametric approach that resembles that of Bajari, Houghton and Tadelis (2014) is implemented.

The first-step regression function takes the following form:

$$\frac{b_{ij}}{\bar{b}_j} = X_{ij}\phi + u_{ij} \tag{19}$$

where the dependent variable is the normalized bid (own score divided by engineer score), and X_{ij} is the combination of contract and bidder characteristics. It is not surprising that the variance of error term increases with the scale of the project if a regression is run of RHS variables on absolute dollar amounts of bids. Hope is that normalization of scores can take away a huge amount of the cross-auction heteroskedasticity.

The error term u_{ij} is assumed iid with distribution $G_u(\cdot)$. Under this assumption, it follows that:

$$H_{ij}(b) \equiv Pr(\frac{b_{ij}}{\bar{b}_j} \leq \frac{b}{\bar{b}_j}) = Pr(X_{ij}\phi + u_{ij} \leq \frac{b}{\bar{b}_j}) \equiv G_u(\frac{b}{\bar{b}_j} - X_{ij}\phi) \tag{20}$$

That is, the distribution of the observed bids can be feasibly identified using the distribution of the estimated residuals $\hat{u}$, and this is done by substituting in the empirical distribution of $\hat{u}$ in place of G. The densities of scores can be obtained by the following way: for each of the normalized scores, form a new distribution by centering the $\hat{u}$'s on each $X_{ij}\hat{\phi}$; get the density estimate for each normalized score; divide the densities of normalized scores by the corresponding engineer score to obtain the estimated densities for the absolute scores. And the estimation results are shown in Table 6.

5.3 Recovering Bidders' Pseudocosts, True Costs and α's

As shown in the above section, estimated residuals $\hat{u}$ and its distribution from the previous regression can identify bidders' pseudocosts. Then, bidders minimized costs can be identified by pseudocost minus usercost times days bid, according to the scoring rule. Furthermore, identification of α's is made possible with knowledge of firms' minimized expected costs and acceleration parameter β along with the estimates of effects of bidder and contract characteristics in the structural estimation. Finally, by referring to the certainty case equilibrium in the theory I am able to predict the q_{FB}'s with the estimates obtained here. Without surprise, the first-best quantities are overall significantly different than q_b and q_c, signaling non-negligible social welfare loss. Detailed discussion of inefficiency is provided in Section 6.

The estimated structural elements are shown in Table 7 which gives a full picture of A+B bidding. Estimated mark-up ratios are on average 21.71% and highly skewed toward zero. According to literature on highway construction industry, profit margins are usually quite small (single digits) in this competitive industry. So I record the median of 10.73% to be in line with previous studies. Material or fixed costs on average almost take up the whole part of true costs of construction, only leaving an average of 7% as acceleration costs. I find this result no surprising since the estimated construction target days by bidders are considerably greater than the days they bid. The discovery of no concrete (and thus expensive) acceleration that is carried out with A+B procurements is one of the defining differences of this paper with previous studies where acceleration is argued to be cheap and affordable with observed significant cut in schedules. My analysis, instead, shows that acceleration is indeed costly even though not much acceleration costs are observed/incurred, precisely due to the reason that bidders are taking advantage of the mechanism by bid skewing and try to avoid genuine acceleration.

6 Policy Analysis

6.1 Evaluation of Current A+B Design

Table 8 shows bid skewing patterns and gives the counts and frequencies of 6 different ranks of q_b, q_c and q_{FB}. The calculated *ex-post* efficiency loss due to the difference in q_c and q_{FB} is given at the end of Table 7 and the number is big. On average, distortions are measured at \$1.73 million, and it is 7.9% of estimated private construction costs. Taken together, these 225 contracts procured A+B incur a total efficiency loss to the society of \$389.25 million in this 11-year period.

Furthermore, bid skewing might also result in failure of *ex-ante* efficiency. If we rank the bidders by their T_0 and compare this rank order with the current bidders, we find that 56 bidders out of 225 with lowest social cost potential (of their respective auctions) got replaced by current winners. That is, the current A+B mechanism assigns jobs to wrong/less efficient bidders at about 25% of the time. A further look into the data shows that almost all of the 56 auction losers (but actual efficient bidders) have considerably lower material/fixed costs, a situation that quite resembles Figure 3. And the 56 current winners are those who skew significantly more compared to the efficient bidders who lost the biddings, by either having a rather low q_b or significantly pushing up q_c or both. Hence society is put at a bad position for that with a fairly good frequency, the auction mechanism fails at detecting the efficient agents, on top of distorting everyone's incentives.

What about second best? Given the expected *ex-post* inefficiency, one might wonder whether second best can be arrived at if we assign the contracts based on their true social costs produced, i.e., T_1. Unfortunately, we still see 27 displacements out of 225 if we rank the bidders by their T_1 and compare the rank order with the current bidders. This 12% displacement rate cannot make us confident enough to say that second best can be achieved with current A+B design.

6.2 Counterfactual Analysis

In this part of the paper, I try to perform a counterfactual analysis where Caltran can change the auction rules and see whether better social outcomes follow.

The most obvious tool that Caltran has is the policy parameter, C_U. One can tell roughly from the theory that as C_U increases, both days bid and target days would decrease as a response mainly because of costly acceleration. A careful look at

Equations (5), (6) and (10), however, shows that C_U not only affects q_b and q_c in the direct way, but also influences them through the effect it has on δ, along with C_D. As mentioned earlier in Section 3, C_D is a one-dimensional variable that captures several factors: reputation considerations, time value of money, and enforcement rate of Caltran, etc. Note also that it is the ratio of C_U and C_D that has an impact on bid skewing. Thus what seems a correct way of predicting how C_U and C_D together change things is to first think about how C_D is potentially affected by C_U. First, greater C_U might mean that project acceleration is more important to Caltran compared to ones with little penalties, thus bidders incur a higher reputation cost of being late. Second, greater C_U pushes up C_D even when bidders account for the time value of money. Last, increasing C_U does not necessarily associate with higher enforcement on Caltran's part, and thus does not guarantee a higher C_D at the same time. Integrating all these effects, I adopt a 'constant-return-to-scale' type of relation between C_U and C_D, that is, C_U affects C_D positively and in a linear way. Thus, the ratio of C_U and C_D remains the same when C_U is increased and the impact on q_b and q_c is simply governed by the acceleration parameter β.

I consider 4 interesting policies Caltran can adopt besides the current one: a 'low-powered' incentive scheme with 50% C_U, even more 'high-powered' bidding rule with 200%C_U, a highly aggressive one with 500%C_U and lastly, forcing A+B back to A-only projects without C_U. Instead of running simulations, I perform simple calculations using structural estimates obtained from the OLS regression. The advantage of such a practice, aside from the sheer simplicity, is that we can stick to the current bidders and auctions which we already know a lot about.

The procedure in the counterfactual is the following: solve for q_b and q_c for different incentives with estimates from previous section; refer to the cost function to calculate acceleration costs and total costs under each incentive schemes with new q_c(for A-only, costs boil down to α's); formulate bidders' pseudocosts by combining total costs of production and B parts; rank the bidders by their pseudocosts for the 3 new incentive schemes and rank according to α's for A-only bids; pin down the winners which are the ones with lowest pseudocosts(or α) for each auction; calculate winners' price bids by deducting their B parts from the second-lowest bidders' pseudocosts if in scoring auctions, second-lowest bidders' α's if A-only auctions (the justification of this is the Revenue Equivalence Theorem), and these price offers are Caltran's payments for the projects; finally, calculate externality (admitting the original C_U as the true per-day externality) and mark-ups as usual.

Table 9 provides the counterfactual results. Under different incentive intensities, days bid q_b changes by relatively small amounts even when incentives are as high as five times, again demonstrating that genuine acceleration comes at significant costs. q_c expands or shrinks in the same way and by the same absolute amounts as q_b, showing that *ex-post* inefficiency cannot be eliminated with changes in auction rules. Total costs increase substantially with greater incentives because of costly acceleration, while the externality sees only a small decrease, rendering the total social costs under 'high-powered' incentive schemes to be significantly higher than that of low- or no-incentive ones. Payment-wise, Caltran faces a much bigger budget challenge when greater incentives are imposed than low or no incentives are at play. And these bigger checks from Caltran are mainly driven by increasing costs, rather than higher mark-up ratios of bidders. Combining the considerations of commuter welfare, private construction cost, and government budget, I argue for procuring schemes with lower incentives than current or even conversion back to traditional contracts. And this policy implication is direct and intuitive since under current framework, bidders' actual construction behaviors are indeed not much different than what they would have been had the projects procured the traditional way.

One thing to note, though, is that we treat the current C_U as the true per-day cost to commuters in the above analysis. Lewis and Bajari (2011a) argue that the current user costs implemented are lower than the true costs to a large degree and they give their estimation of user costs which are multiples of the current ones. If this is true, then the externalities under each policy given in my counterfactual results might be consistently lower than the truth. Simple calculations of externalities and social costs with higher user costs reveal that low-incentive schemes are still preferred even when true user costs go up to five times the current ones. Thus my policy implications and suggestions are robust to this possibility.

6.3 Lessons Learned from A+B Procurement Auctions

At this point, another legitimate question to ask is: is there any room for Caltran to make any changes along other margins than C_U? How about changes in engineer-estimated days q^e? My intuition is that Caltran has to be very careful dealing with this choice variable since q_e strictly sets the upper bound for the time component of the bid, thus tighter q_e might deter entry and thus hurt competition. Detailed analysis of bidder participation and bidder types distribution is needed to draw any policy implication on this matter.

It may seem natural to argue that incentives might be less distorted once Caltran raises the level of contract enforcement. For example, Caltran can demand its resident engineers to keep stricter logs of production progress and cut on unneccessary grants of CCO days or Other days. This effectively raises bidders' perceived penalties of being late and redirects resources to genuine acceleration. One concern here is that it might correct things too much so that bidders get too conservative in bidding, that is, they might skew their bids from under target days to well above and we begin to have inefficiency coming from the other direction.

7 Conclusion

It has been over 20 years of A+B auctions practiced across states since the Federal Highway Administration encouraged DOT's around the U.S. to implement this innovative procuring method. Aiming at aligning social interests with private ones and taking advantage of competitive mechanisms, policy makers embraced A+B design after observing the seemingly large cuts in construction time and increased commuter gains, although with acknowledgement that A+B does put pressure on government budgets. The striking finding in this paper, however, is that bid skewing exists and the current A+B auctions are in fact not quite different with traditional contracting method (A-only). Moreover, self-selected construction time that is different from the expected social-optimal time causes efficiency loss (on average $1.73 million per contract or 7.9% of estimated private construction costs) and the auction mechanism can fail at picking the socially-efficient bidders.

The main take-way from this paper is that design of scoring auctions calls for careful weighing of aspects of incentives in their totality and failure to do so often results in distortions of various sorts. Note that this paper does not aim to question the justification of scoring auctions, but to point out places that have been overlooked by policy makers which can cause real damages. The potential welfare gains from using scoring auctions can only be elicited with thorough investigation of bidding motives, behaviors and environmental elements. Although a delicate matter, there seems plenty room for policy tools to improve the current mechanism and achieve better social outcomes.

CHAPTER TWO

"UNBALANCED BIDS" IN HIGHWAY PROCUREMENTS

1 Introduction

Auctions are very important means of buying projects in government procurement because of the uniqueness of the projects, transparency, and private information of costs. In particular, highway procurement auctions across the U.S. usually take the form of Unit-Price Contracts (UPCs), where the department of transportation (DOT) gives quantity estimates for different tasks (or items) of the project and the bidders attach unit-price bids on each of the tasks and form a single total bid (the inner product of the unit-price vector and the quantity vector). During the construction phase, the DOT makes progress payments, usually monthly, to the contractor for tasks completed in the previous month. Moreover, the payments are determined by the actual quantities incurred although the total bids *ex ante* are evaluated based on the DOT estimates. A forward-looking contractor, who cares about the present value of the stream of payments, would want to structure the unit-price bids in such a way that the expected total present value is maximized. Intuitively, this can be done with shifting more weight toward early tasks and tasks that the bidders believe to overrun compared to the DOT estimates, while maintaining the same total bid. These two types of bid skewing lead to what is generally known in the industry as "unbalanced bids".

The goal of this paper is to detect and quantify bid skewing in highway procurement contracts. In this aim, I start with a theory of bid skewing to present the incentives of bidders to skew the unit bids in certain ways. First of all, I demonstrate that, there is always a positive incentive for bidders to put more weight toward earlier items than later ones since bidders maximize total present values *ex ante* that discount values of later items, while the discounting is not captured by the scoring rule. Second of all, I follow the lead of Athey and Levin(2001), Bajari, Houghton and Tadelis (2014), Miller (2014) on bid skewing along the quantity dimension, which argues that bidders tend to skew more on tasks they believe to overrun compared to the DOT estimates that determine the ranks but not entirely the final payoffs. Private information plays a key part in this type of bid skewing but not for the former type, or "front loading" where the sequence of tasks are common knowledge and certain.

The empirical strategy exploits the availability of the data on unit task costs from the Contract Cost Data book published yearly by Caltran. These unit costs are "the mechanically weighted average of the awarded bidders prices and are affected by location, time, quantity in the job and size of the item" (the Contract Cost Data book, Caltran, 2011-2013). Although much of the individual heterogeneity in item costs are missing, the unit costs can serve as good proxies for costs of all the bidders of all projects within the same year and the common trend of the costs can be captured.

The central hypothesis of this paper is that bidders of UPC projects in equilibrium skew their bids toward early *and* overrun tasks. To test for the hypothesis, I regress logs of unit bid-cost ratios on the binary variable of whether the task is done and paid for in the early half of the project, how much the task is overrun (or underrun), the interaction of the previous two variables, along with other covariates that impact the variations in bid-cost ratios. I find that both the coefficients on "overrun" and the interaction term of "early" and "overrun" are positive and significant, providing support for the theory prediction. Although the effect of "early" itself is not significant, early items do get skewed more if they are overrun. Moreover, there is some evidence suggesting the more aggressive bid skewing behaviors of winners although the evidence is not abundant.

Naturally, one important and interesting question regarding unbalanced bids is whether profitable bid skewing pertain within the auction mechanism or it can be competed away. The answer is yes: bid skewing is always taking place and it has both theoretical and empirical support. Theory shows that no matter how high (or low) the total bid is, bidders always make themselves better off by bid skewing along both dimensions, and this is independent of the extent of competition! As is shown in the regression results, "overrun" and interaction of "early" and "overrun" positively affect the unit bid-cost ratios in the predicted way. Thus, the existence of bid skewing is not a result of poor competition or weak participation of auctions.

Moreover, the overall correct bid skewing on the item quantity variations is suggestive of private information on *ex post* shocks which warrants profitable skewing. In addition, a test of winners' informational rents offers no evidence of private information on quantity variations for winners beyond the amount available to all bidders. It remains to be an interesting and unsolved puzzle why Caltran's quantity estimates are systematically biased compared to all bidders' estimates. Nonetheless, the finding here provides further support on the Private Value (at least partially) as opposed to Common Value assumptions on highway procurement auctions.

To my knowledge, this is the first study to empirically test and quantify the extent of bid skewing, covering both unbalanced bids along the time dimension and the item quantity dimension. The results provide guidance to studies that need to correct for bid skewing to recover costs from bids. Furthermore, this paper offers new evidence on Private Value assumptions of highway procurement auctions from a granular project task level.

This paper is closely related to the emerging literature of bid skewing (Athey and Levin (2001), Ewerhart and Fieseler (2003), Bajari, Houton and Tadalis (2014), Miller (2014), Meng Liu (2015)), with the novelty of directly testing and quantifying bid skewing with granular data on costs. Also, the theory builds upon contributions in scoring auction literature such as Che(1993), Asker and Cantillon(2008), Asker and Cantillon (2010).

The paper is organized as follows. Section 2 presents a theory of "unbalanced bids", highlighting the incentives for bid skewing. Section 3 discusses the data and provides descriptive evidence. Section 4 presents the empirical model with regression results and discusses policy questions. Section 6 concludes.

2 Theory of Unbalanced Bids

2.1 Front Loading

Let risk-neutral bidders be indexed by i, and let contracts be indexed by j.

For simplicity, let there be 2 tasks per project: an early task (which incurs T_{1j} units) that needs to be performed and paid for in Period 1, and a late task (which incurs T_{2j} units) that needs to be performed and paid for in Period 2. The order of tasks, T_{1j}, and T_{2j} are common knowledge to all auction participants. In addition, there is no uncertainty in the quantities T_{1j} and T_{2j}: the department of transportation predicts perfectly the quantities of each task. Let the unit-price bids bidders attach on the tasks be B_{1ij} and B_{2ij}. Then the total bid of Bidder i for Project j is $S_{ij} = B_{1ij}T_{1j} + B_{2ij}T_{2j}$.

Let the bidder- and project-specific discount rate be ρ_{ij}, and let the private unit costs be C_{1ij} and C_{2ij}. Then the present value of payment to bidder i competing with S_{ij} is $P_{ij} = B_{1ij}T_{1j} + \rho_{ij}B_{2ij}T_{2j}$ and the present value of the cost is $C_{ij} = C_{1ij}T_{1j} + \rho_{ij}C_{2ij}T_{2j}$.

Let the indexes be dropped for simplicity. The bidder maximizes her present-value payoff by choose B_1 and B_2:

$$Max\Pi_{B_1,B_2} = P - C = B_1T_1 + \rho B_2T_2 - (C_1T_1 + \rho C_2T_2) \tag{1}$$

subject to $\bar{S} = B_1T_1 + B_2T_2$

With substitution of $\bar{S} = B_1T_1 + B_2T_2$ into (1), the optimization problem becomes one where the bidder decides only on B_2:

$$Max\Pi_{B_2} = \bar{S} - (1-\rho)B_2T_2 - (C_1T_1 + \rho C_2T_2) \tag{2}$$

subject to $B_2 \geq 0$

Apparently, the bidder's optimal choice of B_2 would be $B_2 = 0$, which leads to a final bid of $S = B_1T_1$ where $B_1 > 0$. That is, the sequential feature of the UPC leads to a full skew of the bid on the early portion of the project, and this is true for all bidder types (any realization of C_1, C_2, and ρ). In reality, however, bidders cannot skew their bids as freely as they would like since significant skews away from costs might lead to disqualification from the bidding. Thus, front loading is rewarding yet risky business.

2.2 Uncertainty in Task Quantities

Often seen in practice is that both the DOT and all bidders have imperfect information *ex ante* with regard to the exact quantities of tasks to be used in construction. Thus, all auction participants have to make guesses on the quantities. Let T_{1j} and T_{2j} be the estimate of the DOT on the true quantities t_{1j} and t_{2j}. Also, let bidder i's estimates be Q_{1ij} and Q_{2ij}. All the guesses can be different, but they should "converge" to the true parameters "in the long run". That is,

$$E[T_{1j}] = t_{1j}, E[T_{2j}] = t_{2j}, \forall j$$

And,

$$E[Q_{1ij}] = t_{1j}, E[Q_{2ij}] = t_{2j}, \forall i, j$$

Then the total bid is:

$$S_{ij} = B_{1ij}T_{1j} + B_{2ij}T_{2j}$$

The *ex ante* estimated payment is:

$$P_{ij} = B_{1ij}Q_{1ij} + \rho_{ij}B_{2ij}Q_{2ij}$$

The *ex ante* estimated cost is:

$$C_{ij} = C_{1ij}Q_{1ij} + \rho_{ij}C_{2ij}Q_{2ij}$$

Again, let the indexes be dropped for simplicity. The bidder maximizes her expected present-value payoff by choose B_1 and B_2:

$$Max\Pi_{B_1,B_2} = P - C = B_1Q_1 + \rho B_2Q_2 - (C_1Q_1 + \rho C_2Q_2) \tag{3}$$

subject to $\bar{S} = B_1T_1 + B_2T_2$

With substitution of $\bar{S} = B_1T_1 + B_2T_2$ into (4):

$$Max\Pi_{B_1,B_2} = \bar{S} + B_1(Q_1 - T_1) + B_2(\rho Q_2 - T_2) - (C_1T_1 + \rho C_2T_2) \quad (4)$$

subject to $B_1 \geq 0, B_2 \geq 0$

It is apparent that $\frac{\partial \Pi}{\partial B_1} = Q_1 - T_1$, and $\frac{\partial \Pi}{\partial B_2} = \rho Q_2 - T_2$. Then the bidder's optimal bidding behaviors can be summarized as follows:

1. If $Q_1 - T_1 > \rho Q_2 - T_2$, the bidder fully skews the bid onto Task 1;
2. If $Q_1 - T_1 = \rho Q_2 - T_2$, the direction of skewing is ambiguous;
3. If $Q_1 - T_1 < \rho Q_2 - T_2$, the bidder fully skews the bid onto Task 2.

Since $E(Q_1 - T_1) = E(Q_1) - E(T_1) = t_1 - t_1 = 0$ and $E(\rho Q_2 - T_2) = E(\rho Q_2) - E(T_2) = \rho t_2 - t_2 = (\rho - 1)t_2 < 0$, it is expected that early tasks that are prone to overrun are more likely to be skewed on. The actual direction of the skew, however, should be very much affected by how the item's "overrun" correlates to its "earliness".

2.2.1 Lump Sum Tasks and Variable Quantity Tasks

In reality, some of the tasks have lumpy quantities that are not subject to *ex post* variations. For example, mobilization (setting up shop at the work-site), by definition, has an estimated and realization quantity of 1. Such tasks are risk-free in terms of the quantity variations, but together with variable tasks they still warrants bid skewing and this is well illustrated by an example given in Miller (2014) which is shown in Figure 1.

Consider a project with 2 items: 1 unit of Mobilization and 400 cubic meters of concrete. If the bidder bids at cost, total revenue would be equal to total cost no

	task	bid	q^e	q^a	Score	Revenue	Cost	Profit
Bid at Cost	Mobilization	**600**	1	1	1400	1800	1800	0
	Concrete(m^3)	**2**	400	600				
Skewing Gains	Mobilization	200	1	1	1400	2000	1800	200
	Concrete(m^3)	3	400	600				
Skewing Loss	Mobilization	200	1	1	1400	500	800	-300
	Concrete(m^3)	3	400	100				

Figure 1: Different Bidding Strategies with Two Realizations of Final Quantities (Miller (2014))

matter how large the overrun or underrun is—the bidder is fully immune to risks and losses by bidding at cost. A strategic bidder, however, is interested in structuring her bids in different ways to profit while maintaining the same total bid. Suppose the bidder overbids on the variable task and underbids on the lump sum task, and there is an overrun with the variable task, then the bidder is able to make a positive profit of 200. On the other hand, if the task the bidder overbids on turns out to be less needed, the bidder suffers a loss of 300. Thus, to profitably structure the unit bids over different tasks, one needs to skew more on the tasks that likely overrun and skew less on ones that likely underrun (or lump sum in this case). Clearly, the intuition of bid skewing toward early and overrun items carries with lump sum tasks.

3 Data

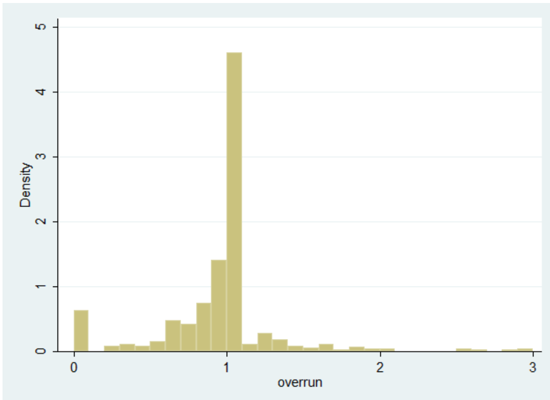
The dataset of this paper was constructed with data publicly available from Caltran website. I randomly chose eight of all pavement contracts that were awarded in the period of 2011-2013. The reason for focusing on pavement contracts is that they represent the most standard and common projects procured by DOTs across the U.S., with a high degree of homogeneity in terms of the work. For each contract, a "Bid

Summary" document in PDF format is downloaded directly from the Caltran website[1] which contains information on basics of the project, total bids and ranks of all the bidders along with bidders' information, list of subcontractors of the winner, and detailed breakdown of the item-level bids for all the bidders. Summary statistics on the contract level are shown in Table 10. On average, a highway pavement contract has an Engineer Estimate at around 5 million dollars with an estimated 70-day construction length. The number of bidders is on average 6.75 with minimum at 4 and maximum at 12, and the number of items, or tasks, for a typical project ranges from 19 to 65 with the average of 40.

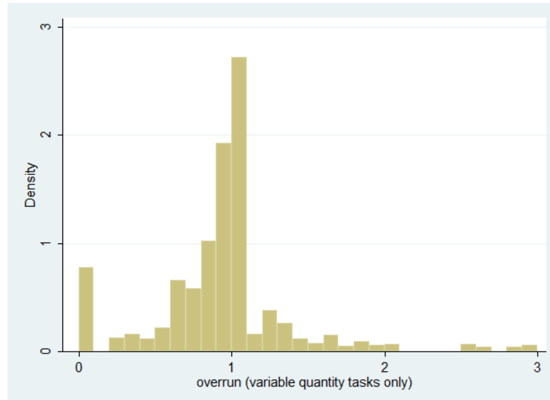
Since most of the analysis of this paper takes place on the item level, patterns of data on the 2084 items bids are relevant and presented in Table 11. The key variable of interest in this study is the ratio of unit bid to unit cost on item level, which is obtained by integrating information on item cost from the Contract Cost Data book published yearly by Caltran. On average, the variable *bcratio* is 1.31 with the standard deviation of 1.37: bid dispersion is sizable, and may not be fully attributed to cost heterogeneity. Since this measure naturally skews to the left, taking logs may lead to more sensible results for later regression analysis.

Another source of the data is the *ex post* payment vouchers collected from Caltran Accounting Office web page which keep records of the final quantities actually used for each item as well as the breakdown of usage by payment periods (usually monthly). *early* is equal to one if more than half of the item value is produced in the early half of the project and zero otherwise. *overrun* is calculated by realized quantity over estimated quantity for each item, and this variable centers at 1.065, meaning an average of 6.5% increasing in the final quantity compared to the original estimate.

[1] "Bid Summary" is located by entering the unique contract number on the "Bid Summary Search" page.



(a) Histogram of "overrun", all tasks



(b) Histogram of "overrun", variable tasks

Figure 2: Histogram of *overrun*

Focusing only on the items with variable quantities and excluding those with lumpy units, this measure has an average of 1.1. As Figure 2 illustrates, there is a significant amount of variation in *overrun*: some of the items are dropped and not used in the construction phase thus the actual quantities are zeros, while others have overruns of multiple of the original estimates. Moreover, the variable *overrun* is heavily skewed to the left with a long tail on the right, which is not surprising since the distribution is, by definition, bounded from below.

4 Empirical Model and Results

4.1 Test for Front Loading

Based on the analysis in Section 2.1, a sensible hypothesis to test for front loading is the following:

Hypothesis 1: *Other things held constant, in equilibrium bidders skew bids more on early tasks than later tasks.*

Let k denote tasks and let $R_{ijk} = B_{ijk}/C_{ijk}$ to denote the task-level bid-cost ratio.

Then the testable implication can be represented by the following regression:

$$R_{ijk} = r_1 + \beta_{11} Early_{ijk} + \beta_{12} No.of Bidders_i + \epsilon_{ijk} \tag{5}$$

where ϵ_{ijk} is the random error at the task level and $No.of Bidders_i$ is the number of bidders bidding on project i. The null hypothesis (No Front Loading) is: $\beta_{11} = 0$, and the alternative hypothesis (Front Loading) is: $\beta_{11} > 0$.

Also, projects differ in scales and magnitudes, thus it is reasonable to argue that bigger and longer projects provide more room for benefits of bid skewing.

Hypothesis 2: *Front loading is more severe in bigger, longer projects.*

Let $Logengest_i$ denote logs of engineer estimates on the project total costs, which is a natural measure of project scales, and let $Early * Logengest_{ijk}$ denote the interaction of $Early_{ijk}$ and $Logengest_i$. Then the testable implication can be represented by the following regression:

$$\begin{aligned} R_{ijk} = r_2 + \beta_{21} Early_{ijk} + \beta_{22} Logengest_i \\ + \beta_{23} Early_{ijk} * Logengest_i + \beta_{24} No.of Bidders_i + \epsilon_{ijk} \end{aligned} \tag{6}$$

where the null hypothesis is: $\beta_{23} = 0$, and the alternative hypothesis is: $\beta_{23} > 0$.

The theory dictates that when holding the total bid constant, bidders can front load their unit bids to increase profit. Thus, in equilibrium winners of the contracts can push down the total bid while maintaining the same profits if they choose to front load. That is, profitable bid skewing is more likely to be associated with higher-ranked bidders.

Hypothesis 3: *Higher-ranked bidders tend to be more aggressive in their skews.*

Let $Winner_{ijk} * Early_{ijk}$ denote the interaction of winners' item bids and whether the item is early, then the regression equation becomes:

$$\begin{aligned} R_{ijk} &= r_3 + \beta_{31}Early_{ijk} + \beta_{32}Logengest_i + \beta_{33}Early_{ijk} * Logengest_i \\ &+ \beta_{34}Winner_{ijk} * Early_{ijk} + \beta_{35}No.of Bidders_i + \epsilon_{ijk} \end{aligned} \quad (7)$$

where the null hypothesis is: $\beta_{34} = 0$, and the alternative hypothesis is: $\beta_{34} > 0$.

Table 13 shows results for the regression equation (5), (6) and (7). The first column tests for Hypothesis 1 with task-level log bid-cost ratio as the dependent variable. Surprisingly, the coefficient of interest on the variable *Early* is negative and statistically significant, favoring the alternative hypothesis of "no front loading" rather than "front loading". Careful thoughts, however, must be given before one jumps into the conclusion of "no front loading" or even "back-end loading". One reasonable suspicion is that the part of "other things held constant" of Hypothesis 1 has not been met, giving rise to possible omitted-variable bias: if the bidder not only skew bids onto early items but also onto items that are prone to overrun, then omitting the variations in overrun could cause the coefficient on *Early* to be biased downward, if *Early* is negatively associated with *Overrun*. And a careful look at the data provides evidence of the negative correlation of these two variables, which is shown in Table 12. Thus, a more justifiable estimate on *Early* can be obtained only when *Overrun* and their interactions are included in the same regression equation.

The positive and significant estimate on the coefficient of $Logengest * Early$ in Column (2) of Table 13 supports the hypothesis that larger projects give more room for profitable front loading. As for Hypothesis 3, the data does not give much support to reject the null: winners are not significantly different than other bidders in terms of how much they skew the bids. Also included in all regressions is the variable *No.of bidders* which gives variations of competitiveness across contracts, and the coefficient is negative and significant across all specifications, suggesting the negative effect of competition on all bid-cost ratios.

4.2 Test for Front Loading *AND* Bid Skewing on Quantity Overruns

Hypothesis 4: *Other things held constant, in equilibrium bidders skew bids more on tasks that are likely to overrun.*

Hypothesis 5: *Early tasks that have larger ex post mis-estimates (by DOT) tend to have larger skews (higher bids).*

Let $Overrun_{ijk}$ to denote the task-level ratio of final quantity and estimated quantity. Then the testable implication can be represented by the following regression:

$$\begin{aligned} R_{ijk} = r_5 + \beta_{51} Early_{ijk} + \beta_{52} Overrun_{ijk} + \beta_{53} Early_{ijk} * Overrun_{ijk} \\ + \beta_{54} No.of Bidders_i + \beta_{55} Logengest_i + \beta_{56} Early_{ijk} * Logengest_i + \epsilon_{ijk} \end{aligned} \tag{8}$$

If the theory is correct, then it is expected that both $\beta_{52} > 0$ and $\beta_{53} > 0$.

Results for the above regression equation are shown in Table 14. For the first specification with all tasks included, the coefficient of *Early* remains significantly negative while the coefficient on *Overrun* is as predicted. What is relieving, however, is that this model is flawed since it includes lump sum quantities which do not allow variations by definition—according to the theory, only bids on variable tasks respond to quantity shocks in the predicted way while bids on lump sum tasks only "passively" absorb the effects of bid skewing from the variable tasks. When only logs of bid-cost ratios of variable tasks are regressed on, the coefficients of both variables of interest are positive and significant: overrun in quantities warrants bid skewing, and moreover

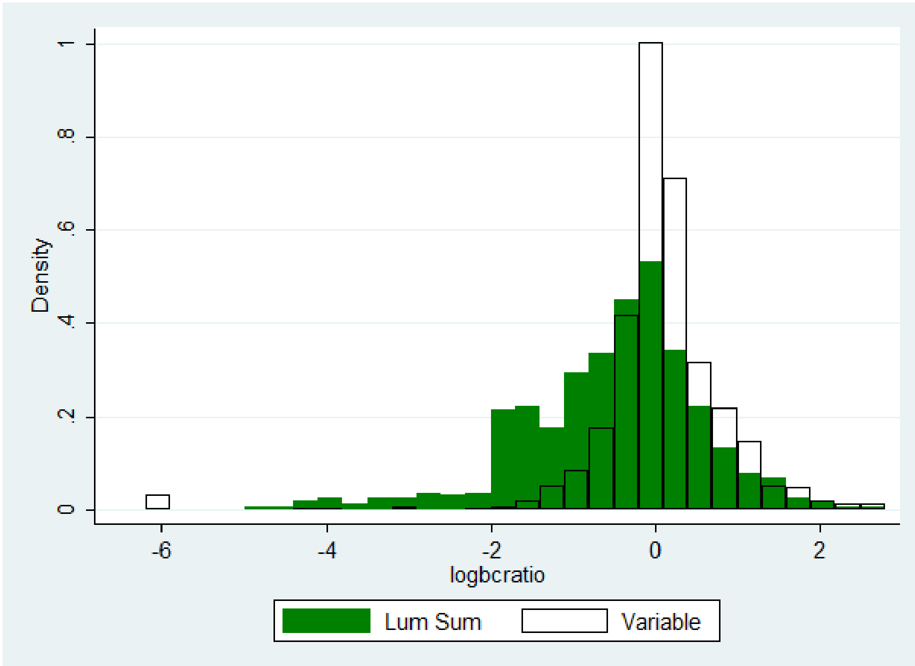


Figure 3: Histograms of *log bid-cost ratio* for lump sum tasks and variable tasks

overrun in the early half leads to additional bid skewing.

Figure 3 gives an overlay of the histograms of *log bid-cost ratio* for lump sum tasks and variable tasks where it is obvious that lump sum tasks has a significant mass below zero. Also it clearly shows that the two distributions are distinct with different means, variances, and overall behaviors. A two-way t test performed on these two groups supports the above finding that *log bid-cost ratios* of lump sum tasks are statistically lower than those of variable tasks.

4.3 Test for Winners' Private Information on Quantity Variations

Now, I want to test whether winning bids reflect *ex ante* private information of shocks on item quantity estimates. In this aim, I interact *Winner* with *Early*, *Overrun*, and

*Early*Overrun*, to capture their differential effects on winners' bid-cost ratios.

$$
\begin{aligned}
R_{ijk} = r_6 &+ \beta_{61} Early_{ijk} + \beta_{62} Overrun_{ijk} + \beta_{63} Early_{ijk} * Overrun_{ijk} \\
&+ \beta_{64} No.ofBidders_i + \beta_{65} Logengest_i + \beta_{66} Early_{ijk} * Logengest_i \\
&+ \beta_{67} Winner_{ijk} * Early_{ijk} + \beta_{68} Winner_{ijk} * Overrun_{ijk} \\
&+ \beta_{69} Winner_{ijk} * Early_{ijk} * Overrun_{ijk} + \epsilon_{ijk}
\end{aligned} \tag{9}
$$

If there are information rents, both β_{68} and β_{69} should be greater than zero.

Table 15 reports results of the above regression: none of β_{67}, β_{68}, or β_{69} is significantly different from zero, indicating that the bidding patterns of winners are not systematically different from all other bidders. Thus there is not enough evidence for private information on quantity variations for winners beyond the amount available to all bidders. One very interesting question arises though, is why Caltran's quantity estimates are systematically biased compared to all bidders' estimates. Nonetheless, the finding here provides further support on the Private Value (at least partially) as opposed to Common Value assumptions on highway procurement auctions[2].

5 Conclusion

The unique feature of unit price bidding of highway procurement auctions across the U.S. gives rise to profitable unbalanced unit bids: shifting more weight toward early tasks to get paid early and tasks that the bidders believe to overrun compared to the DOT estimates, while maintaining the same total bid. As long as the rules regarding UPCs are not changed, bidders have every incentive to skew their bids in these two

[2] Note that the total bid is the inner product of unit costs and estimated quantities, and it is perfectly possible that common values might be present at the unit cost level which the current analysis cannot falsify

directions. Moreover, the overall correct bid skewing on the item quantity variations is suggestive of private information on *ex post* shocks, although it remains to be an interesting and unsolved puzzle why Caltran's quantity estimates are systematically biased compared to all bidders' estimates.

Table 1: Outcomes from Completed Comparable Standard and A+B Projects, 2003-2008, Lewis and Bajari (2011)

	Standard	**A+B**
Contract Days	260.1	171.4*
	(234.1)	(114.4)
Working Days	234.8	171.1
	(210.1)	(115.0)
Weather Days	74.06	80.85
	(71.91)	(81.44)
Other Days	8.13	11.36
	(23.77)	(23.51)
Observations	68	59

Table 2: Summary statistics of Caltran A+B projects, 2003-2013

Contract-level key variables				
Variable	**Mean**	**Std. Dev.**	**Min**	**Max**
Engineer Estimate($M)	26.37	30.58	0.78	274.67
Bid (A part)($M)	23.96	30.02	0.55	445.28
Bid/Engest	0.94	0.22	0.38	1.99
Engineer days	352.43	230.65	45	1550
Days bid	211.66	164.83	20	1550
Bdays/Engdays	0.61	0.21	0.13	1
# of bidders	6.88	2.41	2	14
Usercost($)	14768.78	11907.81	1600	93985
Contract characteristics				
Traffic counts	121373	75527	1425	286750
Distance (miles)	107.33	200.71	0.15	2888
Federal	0.77	0.422	0	1
Bid items	120.01	76.74	11	345
Dbgoal	5.36	5.22	0	29
Proposals	24.92	12.62	4	75
Addendums	2.13	1.83	0	14
Pages	391.49	157.81	132	1413
Design details	84.45	42.89	4	253
Bidder characteristics				
Granite	0.07	0.26	0	1
Diablo	0.05	0.21	0	1
RGW	0.04	0.21	0	1
OCJones	0.04	0.19	0	1
Joint Venture	0.05	0.22	0	1
Fringe firm	0.12	0.33	0	1
Instate	0.97	0.16	0	1
Participation experience	16.28	18.61	0	111
Winning experience	2.78	3.40	0	21
N	1341			

Table 3: Summary statistics of *ex-post* performance variables

Variable	Mean	Std. Dev.	Min	Max
Days bid(q_b)	167.37	135.88	27	813
Actual workdays(q_a)	171.73	141.76	27	813
Days Late ($= q_a - q_b$)	4.99	30.83	-75	167
Late ratio ($= (q_a - q_b)/q_b$)	0.03	0.20	-0.35	1.46
Weather days	108.19	104.82	0	621
Weather days/q^e	0.41	0.45	0	3.42
CCO days	48.59	89.40	-22	999
CCO days/q^e	0.13	0.15	-0.03	0.91
Other days	13.09	56.87	0	661
Other days/q^e	0.05	0.19	0	1.96
N	187			

This table shows the *ex-post* performace variables collected from payment vouchers from 'Major Construction Payment and Information' of Caltran's Accounting Division. In the monthly payment vouchers, the Caltran engineers keep records of how the projects proceed. They do so by counting weather days, the total work days and its break down to actual work days, contract change-order days and other days. Out of these 225 projects, 187 have been completed by Sep 30th, 2014. 78 contracts finished exacly on time, 69 contracts finished early, and 40 projects finished late. Out of the 40 late projects, 17 projects were charged penalties and 12 of them got penalties removed in the end.

Weather days are "Days on which the Contractor is prevented by inclement weather or conditions resulting immediately therefrom adverse to the current controlling operation or operations, as determined by the Engineer, from proceeding with at least 75 percent of the normal labor and equipment force engaged on that operation or operations for at least 60 percent of the total daily time being currently spent on the controlling operation or operations". Although contractors will not be charged for a working days when above conditions for a weather day is met, they can choose to work on the portion of the day when the weather becomes suitable for construction. *Contract change order days (CCO days)* are generally working days when the contractor performs tasks by the change orders that add or deduct work items from the original plan. Normally these days are not counted toward project deadline and the extra work performed is usually compensable. It seems that Caltran has a broad definition of *'Other days'* that are roughly days they grant the contractor as time extension for various reasons. 'Other days' are counted as working days, too.

Table 4: Reduced-form regression of log price bids, days bid and days early

	Log Price	Days Bid	Days Early
Variable	**Coefficient**	**Coefficient**	**Coefficient**
Log C_U	-0.002	-48.620***	6.352
	(0.013)	(7.381)	(6.131)
Number of bidders	-0.025***	-11.728***	0.368
	(0.003)	(1.402)	(1.089)
Log engest	0.918***	68.174***	-9.160**
	(0.011)	(5.528)	(4.068)
Log traffic	0.017**	-4.424*	1.110
	(0.007)	(2.610)	(2.118)
Distance	0.0002***	0.046	-0.044
	(0.00006)	(0.029)	(0.049)
Distance2	-8.00e-08**	4.71e-06	0.00007
	(3.40e-08)	(0.00001)	(0.00009)
Biditems	0.001***	0.751***	0.186
	(0.0002)	(0.147)	(0.136)
Dbgoal	0.002	1.192	-0.271
	(0.002)	(0.983)	(0.644)
Fringe firm	0.022	28.690***	-11.732*
	(0.020)	(9.780)	(6.436)
Granite	0.017	-13.894	19.178*
	(0.025)	(11.211)	(11.134)
Diablo	0.150***	40.079***	4.000
	(0.025)	(13.145)	(9.704)
RGW	0.022	6.679	2.119
	(0.024)	(12.555)	(6.183)
OCJones	-0.048*	4.352	8.393
	(0.028)	(13.718)	(11.562)
JV	0.030	-4.248	-13.667
	(0.025)	(18.836)	(11.521)
Par.experience	-0.002*	-1.275***	-0.447
	(0.001)	(0.451)	(0.374)
Win.experience	-0.006	-8.576***	-1.622
	(0.005)	(2.303)	(2.511)
Win.exp x par.exp.	0.0001**	0.164***	0.029
	(0.00005)	(0.027)	(0.027)
Industry FE	**Y**	**Y**	**N**
Year FE	**Y**	**Y**	**N**
District FE	**Y**	**Y**	**N**
N	1341	1341	187
$\mathbf{R}^2$	0.6999	0.9726	0.1356

Standard errors are in parentheses. *** corresponds to $p < 0.01$, ** for $p < 0.05$, and * for $p < 0.1$.

Table 5: Structural estimation of acceleration

	(1)	(2)	(3)	(4)
Variable	**Coeff.**	**Coeff.**	**Coeff.**	**Coeff.**
Log C_U	-4.565	-11.764**	-11.075**	-10.990**
	(4.679)	(5.320)	(5.325)	(5.307)
Engdays	0.857	0.943	0.650	0.606
	(0.707)	(0.647)	(0.594)	(0.601)
qelnqe	-0.084	-0.100	-0.056	-0.047
	(0.113)	(0.103)	(0.094)	(0.095)
qe2lnqe2	5.21e-06**	5.68e-06***	5.04e-06***	4.88e-06***
	(2.05e-06)	(1.83e-06)	(1.61e-06)	(1.62e-06)
Bigfour x *qelnqe*			0.002	0.005
			(0.004)	(0.005)
Fringe firm x *qelnqe*			0.020***	0.019***
			(0.005)	(0.005)
par.experience x *qelnqe*				-0.00002
				(0 .0002)
Win.experience x *qelnqe*				-0.0005
				(0.001)
Log engest	20.344***	21.000***	20.083***	19.879***
	(4.440)	(4.456)	(4.361)	(4.358)
Log traffic	-4.970***	-6.319***	-5.873***	-5.858***
	(1.892)	(2.150)	(2.110)	(2.103)
Distance	0.003	0.001	0.010	0.008
	(0.020)	(0.021)	(0.021)	(0.021)
Distance2	0.00001	0.00001	0.00001	0.00001
	(8.92e-06)	(9.71e-06)	(9.51e-06)	(9.51e-06)
Biditems	0.318***	0.215**	0.218**	0.217**
	(0.096)	(0.101)	(0.099)	(0.099)
Dbgoal	1.480***	1.107	1.198	1.180
	(0.435)	(0.782)	(0.780)	(0.779)
Fringe firm	16.302***	23.808***	-7.914	-5.378
	(6.037)	(6.483)	(8.190)	(8.621)
Bigfour	21.531***	20.016***	13.900	8.117
	(6.031)	(5.733)	(8.761)	(9.579)
Par.experience	-1.248***	-0.712**	-0.688**	-0.613
	(0.293)	(0.278)	(0.278)	(0.452)
Win.experience	-7.628***	-6.987***	-6.883***	-5.907***
	(1.495)	(1.431)	(1.422)	(2.089)
Win.exp x par.exp	0.133***	0.091***	0.089***	0.088***
	(0.022)	(0.021)	(0.021)	(0.021)
Constant	-137.379***	-128.627**	-111.353*	-110.813*
	(51.585)	(58.629)	(57.179)	(57.106)
N	1341	1341	1341	1341
$\mathbf{R}^2$	0.8240	0.8467	0.8494	0.8496

Model (1) is the baseline model presuming constant $\bar{\delta}$ without year or district fixed effects; Model (2) is the baseline model including year or district fixed effects; Model (3) includes firm type interactions with $q^e ln(q^e)$; Model (4) includes firm type and experience interactions with $q^e ln(q^e)$. Industry fixed effects are included in all models. Year and District fixed effects are included in all models except (1). Standard errors are in parentheses. *** corresponds to $p < 0.01$, ** for $p < 0.05$, and * for $p < 0.1$.

Table 6: OLS regression of normalized scores on contract and bidder characteristics

Variable	**Coeff.**
Distance	0.0002***
	(0.00005)
Distance2	-8.99e-08***
	(2.70e-08)
Log traffic	0.001
	(0.006)
Federal	-0.015
	(0.016)
Bid items	0.001***
	(0.0002)
Dbgoal	0.007***
	(0.002)
Addendums	-0.003
	(0.003)
Pages	0.00009
	(0.0001)
Design details	-0.0002
	(0.0004)
Instate	-0.035
	(0.042)
Fringe firm	0.036*
	(0.019)
Granite	0.026
	(0.024)
Diablo	0.135***
	(0.026)
RGW	0.021
	(0.022)
OCJones	-0.024
	(0.025)
JV	0.041*
	(0.022)
Par.experience	-0.002*
	(0.001)
Win.experience	-0.009**
	(0.004)
Win.exp x par.exp	0.0001***
	(0.00005)
$\mathbf{R}^2$	0.3209
N	1341

The dependent variable is the normalized score: score divided by the engineer score (user-cost*engineer days + engineer estimate). Year, district and work type fixed effects are included. Standard errors are in parentheses. *** corresponds to $p < 0.01$, ** for $p < 0.05$, and * for $p < 0.1$.

Table 7: A broad picture of A+B: estimation of structural elements

Parameter/Variable	**Mean**	**Std. Dev.**	**Min**	**Max**
β	0.091	0.044	-	-
$\beta_0 (= \beta q^e)$	32.07	20.99	4.10	141.04
w	0.0104	-	-	-
$\sigma (= w q^e ln(q^e))$	22.09	17.13	1.78	117.98
$\sigma_N (= w ln(q^e) = \sigma / q^e)$	0.059	0.006	0.039	0.076
δ	-4.42	0.65	-5.64	-2.75
q^e	352.43	230.65	45	1550
q_a(N=187)	174.77	156.72	12	1229
q_b^*	211.86	164.74	20	1550
q_c^*	310.94	236.41	34.11	1912.01
q_{FB}	256.02	168.78	4.13	1144.75
Score($M)	27.56	34.70	0.60	505
Pseudocost($M)	25.52	33.03	0.12	492.32
Total Cost($M)	21.97	28.41	0.11	433.11
Acceleration Cost($M)	0.90	4.05	0	61.30
α($M)	21.07	28.47	0.06	433.11
Acceleration Cost/Total Cost	7.14%	19.60%	0	80.00%
Bid total (A part)($M)	23.96	30.02	0.55	445.28
Ex-ante markup ratio	10.73%(Median)	65.41%	0%	400%
Ex-post efficiency loss($M)	1.73	4.30	0	57.60
N	1341			

Table 7 gives the estimated structural elements and shows a full picture of A+ B bidding. The second block gives the readers an overall impression of firms' choices of days bid and construction target time, with first-best days included for comparison and reference. As is clearly shown, days bid are consistently skewed under construction target time. Estimated mark-up ratios are on average 21.71% and highly skewed toward zero. According to literature on highway construciton industry, profit margins are usually quite small (single digits) in this competitive industry. So I record the median of 10.73% to be in line with previous studies. Material or fixed costs on average almost take up the whole part of true costs of construction, only leaving an average of 7% as acceleration costs. The calculated *ex-post* efficiency losses due to differences in q_c and q_{FB} are given at the end. On average, distortions are measured at $1.73 million, and it is 7.9% of estimated private construction costs. Taken together, these 225 contracts procured A+B way incur a total efficiency loss to the society of $389.25 million in this 11-year period.

Table 8: Count and frequency of various q_b, q_c and q_{FB} ranks

Rank	**Count**	**Freqency**
$q_b < q_{FB} < q_c$	679	50.6%
$q_{FB} < q_b < q_c$	346	25.8%
$q_b < q_c < q_{FB}$	316	23.6%
$q_c < q_b < q_{FB}$	0	0%
$q_c < q_{FB} < q_b$	0	0%
$q_{FB} < q_c < q_b$	0	0%

Table 8 shows the counts and frequencies of 6 different ranks of q_b, q_c and q_{FB}. No bid skewing such that $q_c < q_b$ is observed.

Table 9: Counterfactual analysis

Variable/Outcome	Current	50%C_U	200%C_U	500%C_U	A-only
q_b	211.66	219.28	204.04	193.97	-
	(164.83)	(164.83)	(164.83)	(164.83)	-
q_c	310.94	318.56	303.32	293.25	352.43
	(236.41)	(236.41)	(236.41)	(236.41)	(230.65)
q_{FB}	256.02	256.02	256.02	256.02	256.02
	(168.78)	(168.78)	(168.78)	(168.78)	(168.78)
Accl. Cost($M)	0.90	0.45	1.80	4.50	0
	(4.05)	(2.03)	(8.10)	(20.30)	-
Total cost($M)	21.97	21.52	22.87	25.56	21.07
	(28.41)	(28.37)	(28.91)	(33.46)	(28.47)
Externality($M)	5.27	5.39	5.16	5.01	5.88
	(7.94)	(8.01)	(7.88)	(7.79)	(7.70)
Total social cost($M)	27.24	26.90	28.03	30.58	26.94
	(34.99)	(35.01)	(35.35)	(39.09)	(34.61)
Caltran payment (N=225, $M)	22.14	20.50	22.15	24.17	19.68
	(27.92)	(28.50)	(29.30)	(31.05)	(28.48)
Markup ratio (Median, N=225)	10.73%	11.53%	8.03%	9.36%	11.40%

Table 9 provides the counterfactual results. Under different incentive intensities, days bid q_b changes by relatively small amounts even when incentives are as high as five times, again demonstrating that genuine acceleration comes at significant costs. q_c expands or shrinks in the same way and by the same absolute amounts as q_b, showing that *ex-post* inefficiency cannot be eliminated with changes in auction rules. Total costs increase substantially with greater incentives because of costly acceleration, while the externality sees only a small decrease, rendering the total social costs under 'high-powered' incentive schemes to be significantly higher than that of low- or no-incentive ones. Payment-wise, Caltran faces a much bigger budget challenge when greater incentives are imosed than low or no incentives are at play. And these bigger checks from Caltran are mainly driven by increasing costs, rather than higher mark-up ratios of bidders. Combining the considerations of commuter welfare, private construction cost, and government budget, I argue for procuring schemes with lower incentives than current or even conversion back to traditional contracts. And this policy implication is direct and intuitive since under current framework, bidders' actual construction behaviors are indeed not much different than what they would have been had the projects procured the traditional way.

One thing to note, though, is that we treat the current C_U as the true per-day cost to commuters in the above analysis. Lewis and Bajari (2011a) argue that the current user costs implemented are lower than the true costs to a large degree and they give their estimation of user costs which are multiples of the current ones. If this is true, then the externalities under each policy given in my counterfactual results might be consistently lower than the truth. Simple calculations of externalities and social costs with higher user costs reveal that low-incentive schemes are still prefered even when true user costs go up to five times the current ones. Thus my policy implications and suggestions are robust to this possibility.

Table 10: Contract-level Summary Statistics

Variable	**Mean**	**Std. Dev.**	**Min**	**Max**
Engineer Estimate($ M)	5.219	5.554	0.526	16.758
Engineer Days Estimate	70.625	30.171	35	120
Number of Bidders	6.75	2.712	4	12
Number of Items	39.375	16.681	19	65
N	8			

Table 11: Item-level Summary Statistics

Variable	**Mean**	**Std. Dev.**	**Min**	**Max**	**N**
Bcratio(=Unit Bid / Unit Cost)	1.309	1.373	0.002	15.596	2084
Log(bcratio)	-0.085	0.971	-6.11	2.747	2084
Overrun	1.065	1.405	0	20.881	2084
Overrun(items with variable quantities only)	1.1	1.636	0	20.881	1528
Early	0.643	0.479	0	1	1951

Table 12: Correlation between *Early* and *Overrun*

	Overrun	Overrun(<10)	Overrun (Variable Q)	Overrun (Variable Q and <10)
Early	-0.037	-0.103	-0.025	-0.108
N	1951	1935	1411	1395

Table 13: Test for "Front Loading"

	(1)	(2)	(3)
Early	-0.147***	-5.698***	-5.698***
	(0.044)	(0.680)	(0.678)
No. of Bidders	-0.026**	-0.028***	-0.028***
	(0.011)	(0.011)	(0.011)
Log engest		-0.056	-0.056
		(0.046)	(0.047)
Log engest * early		0.363***	0.363***
		(0.044)	(0.044)
Winner * early			0.001
			(0.104)
Bidder FE	**Y**	**Y**	**N**
N	1951	1951	1951
$\mathbf{R}^2$	0.064	0.109	0.109

Standard errors are in parentheses. *** corresponds to $p < 0.01$, ** for $p < 0.05$, and * for $p < 0.1$.

Table 14: Test for "Front Loading" with Quantity Overrun

	(1) All tasks	(2) Variable Tasks Only
Early	-5.191***	-0.943
	(0.701)	(0.753)
Overrun	0.053***	0.030**
	(0.014)	(0.014)
Early * overrun	0.009	0.040**
	(0.017)	(0.017)
No.of bidders	-0.028**	-0.025*
	(0.011)	(0.014)
Log engest	-0.034	-0.026
	(0.048)	(0.053)
Log engest * early	0.330***	0.061
	(0.045)	(0.048)
Bidder FE	**Y**	**Y**
N	1951	1411
$\mathbf{R}^2$	0.117	0.076

Standard errors are in parentheses. *** corresponds to $p < 0.01$, ** for $p < 0.05$, and * for $p < 0.1$.

Table 15: Test for Private Information on Quantity Variations

	(1) All tasks	(2) Variable Tasks Only
Early	-5.174***	-0.934
	(0.701)	(0.753)
Overrun	0.061***	0.036**
	(0.016)	(0.015)
Early * overrun	0.0004	0.034*
	(0.018)	(0.018)
No.of bidders	-0.029***	-0.026*
	(0.011)	(0.014)
Log engest	-0.034	-0.026
	(0.048)	(0.053)
Log engest * early	0.329***	0.060
	(0.045)	(0.048)
Winner * early	-0.030	-0.038
	(0.115)	(0.136)
Winner * overrun	-0.049	-0.039
	(0.031)	(0.029)
Winner * early * overrun	0.056	0.042
	(0.038)	(0.037)
Bidder FE	**Y**	**Y**
N	1951	1411
$\mathbf{R}^2$	0.117	0.077

Standard errors are in parentheses. *** corresponds to $p < 0.01$, ** for $p < 0.05$, and * for $p < 0.1$.

APPENDICES

Appendix A

Derivation of First-Order Conditions (5) and (6) of Chapter One

Recall that the agent's optimization problem is the following:

$$\begin{aligned} Max\Pi_{q_b,q_c} &= \bar{S} - C_U q_b - E_{q_a}[C(q_a;q^e,\alpha,\beta)] - E_{q_a}[D(q_a,q_b,C_D)] \\ &= \bar{S} - C_U q_b - \int_{q^{cp}}^{q^e} (\alpha + e^{\beta(q^e-t)}) f(t;q_c)\mathrm{d}t \\ &- \int_{q_b}^{q^e} C_D(t-q_b) f(t;q_c)\mathrm{d}t \end{aligned}$$

I. Given any q_c, find q_b such that:

$$\frac{\partial}{\partial q_b}(-C_U q_b) + \frac{\partial}{\partial q_b}(-\int_{q_b}^{q^e} C_D(t-q_b) f(t;q_c)\mathrm{d}t) = 0$$

$$\Rightarrow C_U = \int_{q_b}^{q^e} C_D f(t;q_c)\mathrm{d}t)$$

$$\Rightarrow C_U = C_D[1 - F(q_b^*;q_c^*)]$$

II. Given any q_b, find q_c such that:

$$\frac{\partial}{\partial q_c}(-\int_{q^{cp}}^{q^e}(\alpha+e^{\beta(q^e-t)})f(t;q_c)\mathrm{d}t)+\frac{\partial}{\partial q_c}(-\int_{q_b}^{q^e}C_D(t-q_b)f(t;q_c)\mathrm{d}t)=0$$

$$\Rightarrow\frac{\partial}{\partial q_c}[\alpha+\int_{q^{cp}}^{q^e}e^{\beta(q^e-t)}f(t;q_c)\mathrm{d}t]+\frac{\partial}{\partial q_c}\int_{q_b}^{q^e}C_D(t-q_b)f(t;q_c)\mathrm{d}t=0$$

$$\Rightarrow\frac{\partial}{\partial q_c}\int_{q^{cp}}^{q^e}e^{\beta(q^e-t)}f(t;q_c)\mathrm{d}t+\frac{\partial}{\partial q_c}\int_{q_b}^{q^e}C_D(t-q_b)f(t;q_c)\mathrm{d}t=0$$

$$\Rightarrow\frac{\partial}{\partial q_c}(e^{\beta q^e}\int_{q^{cp}}^{q^e}e^{-\beta t}f(t;q_c)\mathrm{d}t)-\frac{\partial}{\partial q_c}(C_Dq_b\int_{q_b}^{q^e}f(t;q_c)\mathrm{d}t)+\frac{\partial}{\partial q_c}\int_{q_b}^{q^e}C_Dtf(t;q_c)\mathrm{d}t=0$$

$$\Rightarrow\frac{\partial}{\partial q_c}(e^{\beta q^e-\beta q_c+\frac{1}{2}\sigma^2\beta^2})-\frac{\partial}{\partial q_c}(C_Dq_b(1-F(q_b;q_c))-\frac{C_D}{\sqrt{2\pi}\sigma}\int_{q_b-q_c}^{q^e-q_c}(u+q_c)e^{-\frac{1}{2\sigma^2}u^2}\mathrm{d}t=0$$

where $\int_{q^{cp}}^{q^e}e^{-\beta t}f(t;q_c)\mathrm{d}t$ is the moment generating function for the normal random variable. With change of variable $u=t-q_c$,

$$\Rightarrow\frac{\partial}{\partial q_c}(e^{\beta q^e-\beta q_c+\frac{1}{2}\sigma^2\beta^2})-\frac{\partial}{\partial q_c}(C_Dq_b(1-F(q_b;q_c))-\frac{\partial}{\partial q_c}(\frac{C_D\sigma}{\sqrt{2\pi}}e^{-\frac{1}{2\sigma^2}(q^e-q_c)^2})$$
$$+\frac{\partial}{\partial q_c}(\frac{C_D\sigma}{\sqrt{2\pi}}e^{-\frac{1}{2\sigma^2}(q_b-q_c)^2})+\frac{\partial}{\partial q_c}(C_Dq_c(1-F(q_b;q_c))=0$$

$$\Rightarrow-\beta e^{\beta q^e-\beta q_c+\frac{1}{2}\sigma^2\beta^2}-\frac{\partial}{\partial q_c}(C_D(q_b-q_c)(1-F(q_b;q_c))-\frac{\partial}{\partial q_c}(\frac{C_D\sigma}{\sqrt{2\pi}}e^{-\frac{1}{2\sigma^2}(q^e-q_c)^2})$$
$$+\frac{\partial}{\partial q_c}(\frac{C_D\sigma}{\sqrt{2\pi}}e^{-\frac{1}{2\sigma^2}(q_b-q_c)^2})=0$$

Note that $C_U=C_D[1-F(q_b;q_c)]$ from Part I.

$$\Rightarrow-\beta e^{\beta q^e-\beta q_c+\frac{1}{2}\sigma^2\beta^2}-\frac{\partial}{\partial q_c}(C_U(q_b-q_c))-\frac{C_D}{\sqrt{2\pi}\sigma}e^{-\frac{1}{2\sigma^2}(q^e-q_c)^2}(q^e-q_c)$$
$$+\frac{C_D}{\sqrt{2\pi}\sigma}e^{-\frac{1}{2\sigma^2}(q_b-q_c)^2}(q_b-q_c)=0$$

$$\Rightarrow -\beta e^{\beta q^e - \beta q_c + \frac{1}{2}\sigma^2\beta^2} + C_U - C_D f(q_e; q_c)(q^e - q_c) + C_D f(q_b; q_c)(q_b - q_c) = 0$$

Last, let us assume that $f(q_e; q_c)$ is sufficiently small that it is negligible. Thus:

$$C_U(1 + \frac{C_D}{C_U} f(q_b; q_c)(q_b - q_c))/e^{\frac{1}{2}\sigma^2\beta^2} = \beta e^{\beta(q^e - q_c)}$$

Combining the results in both parts and we have:

$$C_U(1 + \frac{C_D}{C_U} f(q_b^*; q_c^*)(q_b^* - q_c^*))/e^{\frac{1}{2}\sigma^2\beta^2} = \beta e^{\beta(q^e - q_c^*)}$$

$$\frac{C_U}{C_D} = 1 - F(q_b^*; q_c^*)$$

Appendix B

Derivation of Equation (16) of Chapter One

Recall that Equation (15) is:

$$C_{Uj}(1+\frac{f_{ij}(q^*_{bij};q^*_{cij})}{1-F_{ij}(q^*_{bij};q^*_{cij})}(q^*_{bij}-q^*_{cij})) = e^{\frac{1}{2}\sigma^2_{ij}\beta^2_0/(q^e_j)^2}\frac{\beta_0}{q^e_j}e^{\beta_0\frac{(q^e_j-q^*_{cij})}{q^e_j}}e^{X_{ij}\theta_\beta+\epsilon_{\beta ij}}$$

Taking logs on both sides (dropping indexes for conveniece) leads to:

$$lnC_U+ln(1+\frac{f(q^*_b;q^*_c)}{1-F(q^*_b;q^*_c)}(q^*_b-q^*_c)) = \frac{1}{2}\sigma^2\beta^2_0/(q^e)^2+ln(\frac{\beta_0}{q^e})+\beta_0\frac{(q^e-q^*_c)}{q^e}+X\theta_\beta+\epsilon_\beta$$

where

$$ln(1+\frac{f(q^*_b;q^*_c)}{1-F(q^*_b;q^*_c)}(q^*_b-q^*_c)) = ln(1-F(q^*_b;q^*_c)+f(q^*_b;q^*_c)(q^*_b-q^*_c))-ln(1-F(q^*_b;q^*_c))$$

Let $g(q^*_c)=1-F(q^*_b;q^*_c)+f(q^*_b;q^*_c)(q^*_b-q^*_c)$, and $h(q^*_c)=1-F(q^*_b;q^*_c)$,

Then, $g(q^*_b)=1-F(q^*_b;q^*_b)+f(q^*_b;q^*_b)(q^*_b-q^*_b)=1-1/2+0=1/2$, and $h(q^*_b)=1-F(q^*_b;q^*_b)=1/2$.

Now rearrange and take Taylor expansion of the term $ln(1+\frac{f(q^*_b;q^*_c)}{1-F(q^*_b;q^*_c)}(q^*_b-q^*_c))$ at $q^*_c=q^*_b$ up to the second order:

$$ln(1-F(q^*_b;q^*_c)+f(q^*_b-q^*_c)) \approx ln(g(q^*_b))+\frac{1}{g(q^*_b)}(g(q^*_c)-g(q^*_b))-\frac{1}{2g(q^*_b)^2}(g(q^*_c)-g(q^*_b))^2$$

$$=ln(\frac{1}{2})+1-2F(q^*_b;q^*_c)+2f(q^*_b;q^*_c)(q^*_b-q^*_c)-2(1/2-F(q^*_b;q^*_c)+f(q^*_b;q^*_c)(q^*_b-q^*_c))^2$$

And,

$$ln(1-F(q_b^*;q_c^*)) \approx ln(h(q_b^*)) + \frac{1}{h(q_b^*)}(h(q_c^*)-h(q_b^*)) - \frac{1}{2h(q_b^*)^2}(h(q_c^*)-h(q_b^*))^2$$
$$= ln(\frac{1}{2}) + 1 - 2F(q_b^*;q_c^*) - 2(1/2 - F(q_b^*;q_c^*))^2$$

Safely ignoring the difference between the two squared terms, we have:

$$ln(1+\frac{f(q_b^*;q_c^*)}{1-F(q_b^*;q_c^*)}(q_b^*-q_c^*)) \approx 2f(q_b^*;q_c^*)(q_b^*-q_c^*)$$

Note that the absolute magnitude of the term $2f(q_b^*;q_c^*)(q_b^*-q_c^*)$ is just the area in the pdf (centered at q_c^*) surrounded by q_b^*, $-q_b^*$, $f(q_b^*;q_c^*)$, and $f(-q_b^*;q_c^*)$. And this area can be approximated by the triangle connecting the pionts q_b^*, $-q_b^*$, and $f(q_c^*;q_c^*)$. Thus,

$$ln(1+\frac{f(q_b^*;q_c^*)}{1-F(q_b^*;q_c^*)}(q_b^*-q_c^*)) \approx \frac{1}{\sqrt{2\pi}\sigma}(q_b^*-q_c^*)$$

Taking this into the second equation of this section gives:

$$lnC_U + \frac{1}{\sqrt{2\pi}\sigma}(q_b^*-q_c^*) = \frac{1}{2}\sigma^2\beta^2 + ln\beta + \beta(q^e-q_c^*) + X\theta_\beta + \epsilon_\beta$$

And finally Equation (16) is obtained with $q_{bij}^* - q_{cij}^* = \delta_{ij}\sigma_{ij}$, $\sigma_{ij}^N = \sigma_{ij}/q_j^e$ and rearranging:

$$q_{bij}^* = -\frac{1}{\beta}lnC_{Uj} + \delta_{ij}\sigma_{ij} + \frac{1}{2}\beta(\sigma_{ij})^2 + q_j^e + \frac{ln(\beta)}{\beta} - \frac{1}{\sqrt{2\pi}\beta}\delta_{ij} + \frac{1}{\beta}X_{ij}\theta_\beta + \frac{1}{\beta}\epsilon_{\beta ij}$$

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