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The trashy side of baseball: An econometric analysis of the Houston Astros cheating scandal.

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Abstract

In this paper, we investigate the efficacy of the cheating scheme employed by the Houston Astros the 2017 Major League Baseball season, in which they won the championship. We present evidence that the cheating scheme profoundly affected player performance and increased the number of wins the Astro's accumulated in the 2017 season. We analyze individual player performance in the 2017 season to estimate the average individual benefit to the Astros players from the scheme. We use these estimates to calculate the benefit to the team in terms of offensive performance and the cumulative impact on the team's overall performance. We estimate the team won at least 2-3 games and potentially as many as 15 games they might not have otherwise won had they not cheated. Our analysis presents the first estimates of the benefits of this momentous event.

Our preferred Secondary JEL Category is Z2: Sports Economics
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1. Introduction

Baseball has a history of cheating: the Black Sox, Pete Rose, and the steroid era[1] all mar baseball's past. The most recent dark chapter unfolded before the 2020 Major League Baseball season. Late in 2019, the Houston Astros were accused of using video cameras to steal opponent signs during their championship 2017 season. A Major League Baseball investigation confirmed the allegations of cheating (MLB.com, 2020). The League penalized the Astros' organization, Astros' general manager, Jeff Lunhow, and manager, AJ Hinch. More importantly, the confirmation of cheating tainted the Astros' 2017 World Series Championship (Rosenthal and Drellich 2019).

The Astro's cheating scheme is not the first in professional sports. Duggan and Levitt (2002) provided economic and statistical evidence that Sumo wrestling matches were often rigged. Sumo wrestling rules provide the opportunity for individuals wrestlers to gain by swapping victories in certain situations. Duggan and Levitt's empirical work found evidence that such swapping was taking place.

Becker (1968) provides the economic framework for the evaluation of cheating in sports. Becker argues cheating will increase as the benefit of cheating rises or when the probability of being caught falls. Therefore, those who seek to gain an advantage from cheating will design a scheme to maximize the benefit from cheating and minimizes the chances of getting caught. The Astro's cheating scheme fits this formula.

The focus of baseball is the competition between the batter and the pitcher. The pitcher seeks to get the batter "out" by causing him to miss three pitches or by inducing weak contact enabling the defenders to retire the batter on the basepaths. To obtain an out, the pitcher uses various pitch types and pitch locations to disrupt the batter's ability to hit the pitch. The batter's uncertainty about the pitcher's intentions on any given pitch is paramount to the pitcher's success. The pitcher and his catcher, communicate via the catcher's hand signals. These hand signals tell the pitcher which pitch type and where to throw. For a discussion on the process, value, and ethics of sign stealing baseball see Barna (2019).

The Astros positioned video cameras in center field of their home stadium and trained them to steal the opponent's catcher's signs to the pitcher. They then conveyed this information in real-time to an operator behind their team's dugout who used decoding software and audible signals to communicate the pitch information to the batter in time for him to react to the pitch.

Knowing the pitcher's intended pitch and location is an enormous advantage for the batter. The batter no longer needs to discern between pitch types and can then predict the pitch's eventual location relative to the strike zone based on relative movement tendencies of different pitches. The value of this is high because the act of deciding whether or not to swing at a pitch, and the ability to hit it, happens during an extremely short time frame, as short as 375 milliseconds (Takeuchi and Inomata, 2009).

[1] Tynes (2006)

The 2017 championship Astros had the most prolific single-season offensive output at the time.[2] Would the team have won the World Series or even made the playoffs without cheating? Despite the potential benefits and scope of cheating, Major League Baseball did not expunge or even place a qualification on the Astros' championship season. Therefore, the league did not think the cheating had a decisive impact on the season. In contrast, this paper presents evidence that the cheating scheme had a profound effect on player performance and increased the number of wins the Astro's accumulated.

2. Data

An extensive data set of pitch and at-bat characteristics is merged with a novel data set that tracks the audible signal to the batter, given by an operator behind the dugout banging on the trash can. In pairing the occurrence and non-occurrence of the signal with the characteristics of each encounter, the effect of the real-time information about the pitch is quantified. Detailed information about each pitch's characteristics and outcome with and without the cheating signal, is a unique and rich resource allowing for careful and precise measurement of the Astro’s cheating effectiveness.

Bill Petti's open-access R program *baseballr* provides information about each plate appearance. Petti’s package scrapes data from FanGraphs.com and Baseball-Reference.com, creating an exhaustive data set with measures over select time frames. Specifically, it scrapes data regarding pitch speed, pitch movement, pitch location, launch speed of a struck ball, launch angle, and other characteristics about each plate appearance's outcomes. These data are paired with Tony Adams' databases of the audible cheating signal-the trash can 'bang'. Estimation techniques coupled with this data are used to quantify the Astros' overall season benefit resulting from the illicit strategy.

Adams' data reveals two distinct regimes for the audible bang signal. The first regime appears to be a 'training' period, starting with the first game of the regular season, April 3rd, against the Seattle Mariners to the May 24th game against the Detroit Tigers. During this time, there are an average of two bangs heard each game. However, after May 28th to the end of the regular season, the average increases immediately to 29 audible signals per game, implying more frequent use of the system. The two regimes are seen clearly in Figure 1, which also demonstrates the signaling scale throughout the 2017 season. It is crucial to note that signals only occur in home games.

[2] As measured by weighted runs created (wRC+). wRC+ quantifies a batter’s offensive performance by weighting their individual offensive outcomes by the expected run value of that offensive outcome. https://library.fangraphs.com/offense/wrc/

Figure 1: Tony Adams Audible Bang Signal Data

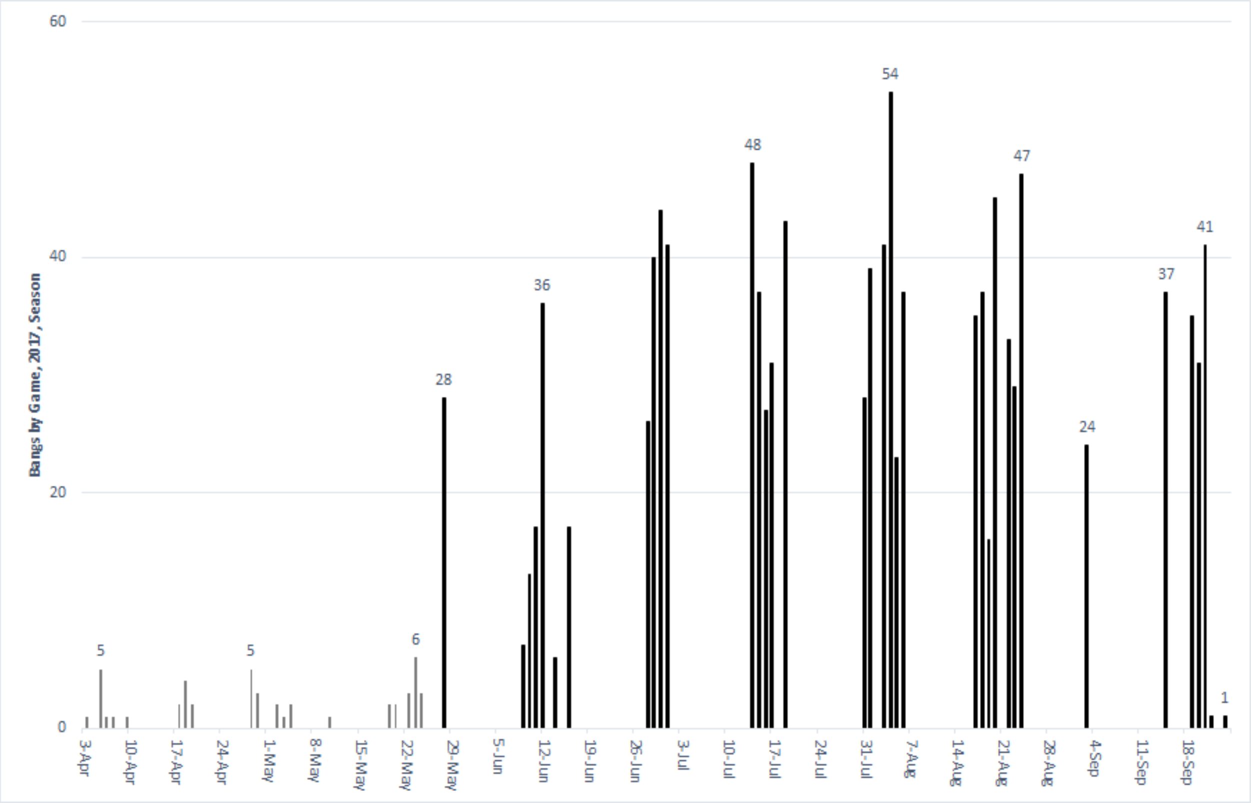


Figure 2 reports the percentages of pitches with an audible signal observed at any time during the plate appearance by inning. The pattern is consistent with a well-considered strategy of cheating. There were few signals in the first inning because opponent hand signals, known as signs, needed to be discovered and cataloged. Thus, the Astros had a lower frequency of audible signals during the first inning. As the game progresses, the frequency of the signal rises. Then, on average, signal use decreases late in games since the value of cheating is small if the outcome of the game is not in question. The frequency of audible signals increases again if the game goes to a 10th inning. A 10th inning spike is expected since the value of cheating is likely at its highest during this time. The home team bats last, so the game is in "sudden death." Perhaps surprisingly at first glance, if the game extends to a 12th inning, the occurrence of the cheating signal drops. Why might the signal drop if the 11th and 12th inning may be “sudden death”? After the 10th inning, many fans leave the stadium, and a drop in noise makes the audible bang signal much clearer and increases the likelihood of someone discovering the cheating scheme. These summary statistics imply a well thought out strategy employed with discipline and rigor.

Figure 2: Frequency of Audible Signals Per Inning

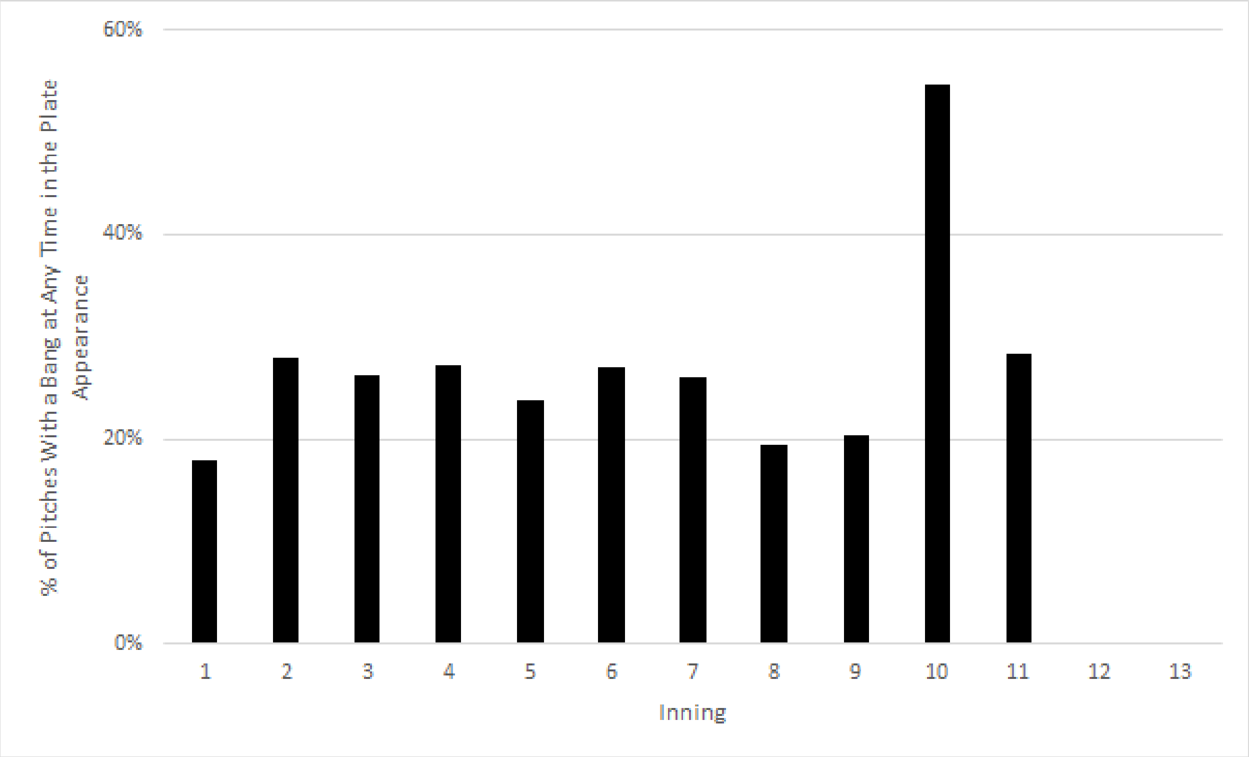
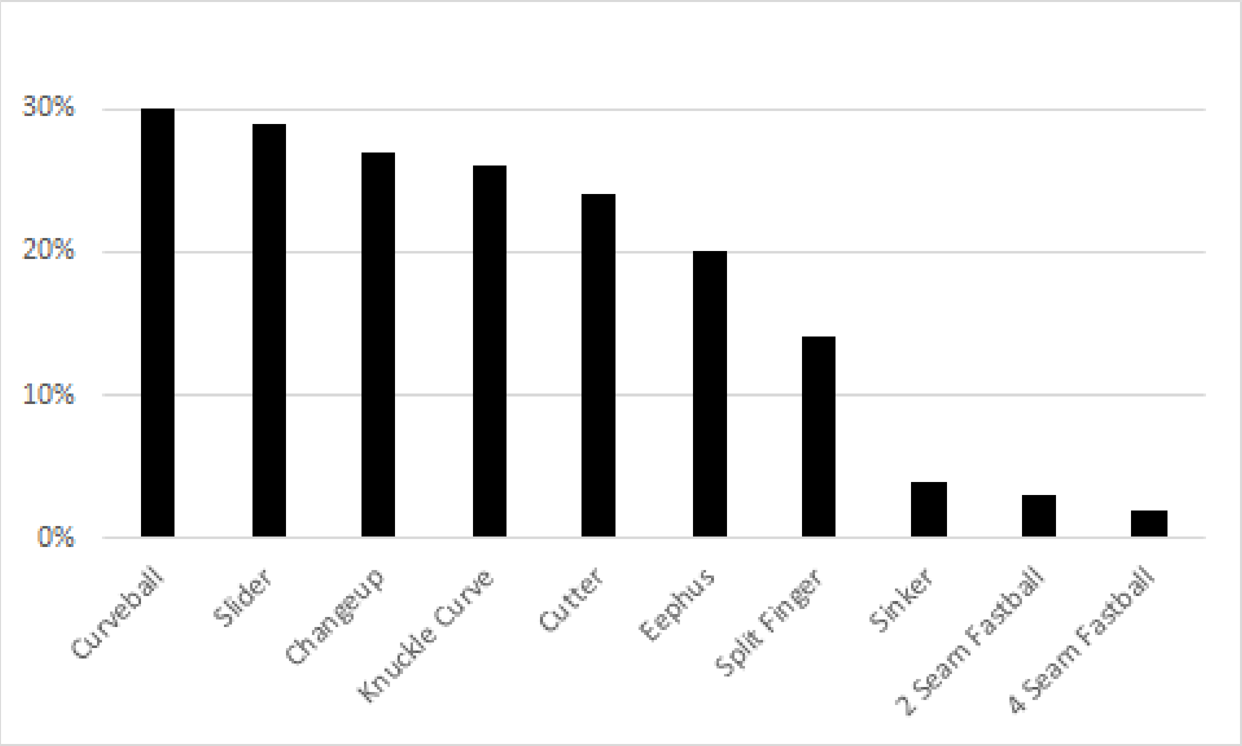


Figure 3 reports the frequency of audible signals per type of pitch. The audible signal produces inside information for the batters on the type of pitch to expect. Not all pitcher repertoires include all types of pitches, so the Astros design the system to help batters distinguish the pitcher's fastball from their main off-speed pitch. Some pitchers feature more than one off-speed pitch, which the Astros' operator differentiates by producing multiple consecutive audible signals. A common scheme is to give one signal bang for a slider (a type of breaking pitch), two for a changeup (typically a straighter and slower pitch to disrupt the batter's timing), and no signal for a fastball. Thus, signals occur on types of pitches where "inside information" matters most. Figure 3 highlights that the Astros commonly employ the scheme against various kinds of off-speed pitches and generally do not for fastball variants (sinkers, two-seamers, and four-seamers). The audible, real-time signal is valuable for breaking pitches. The distribution of the signals given by pitch confirms this.

Figure 3: Audible Signal and Type of Pitch



A summary glance of the data set suggests that the Astros employed the cheating scheme to help batters identify the pitch type that was coming next. This complex process developed throughout the season and within each game. By the middle of the 2017 season, it was consistently and often. The most common offspeed pitches were signaled 20-30% of the time at home games. Further analysis in this paper determines the marginal benefit of using the strategy and quantifies the Houston Astros' advantage during its first World Series Championship season in the next section.

3. Estimation and Results

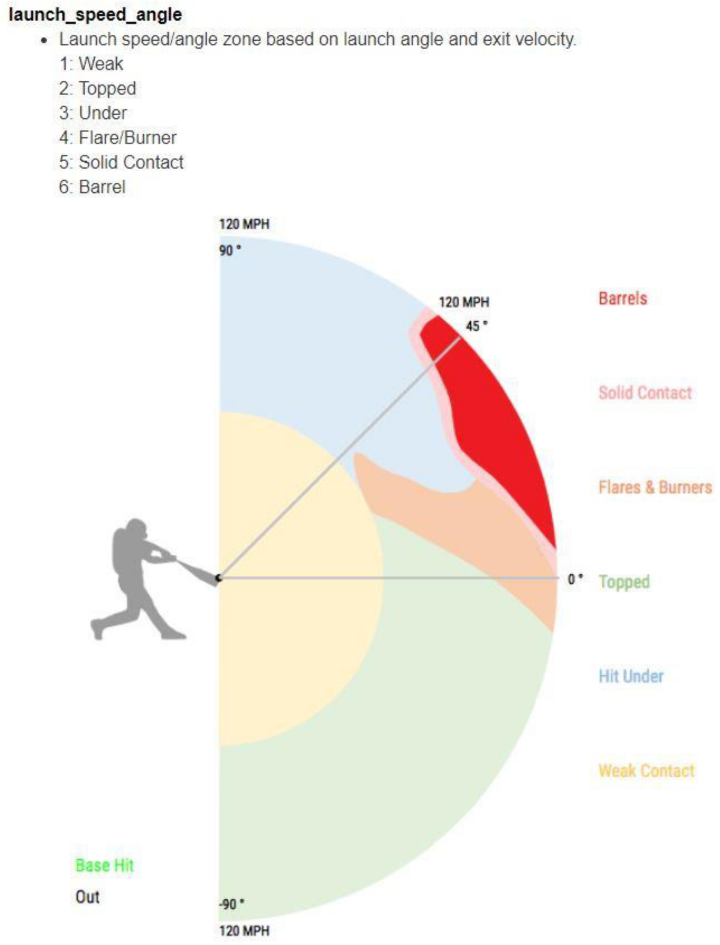
Batters control two essential factors of their plate appearance outcomes: the speed and vertical angle at which the ball leaves the bat. Defenders position themselves around the baseball diamond to cover the field. The batter tries to hit the ball to places on the field where fielders are not, and the pitcher attempts to throw pitches that force the ball to be hit to areas defended by the fielders. At the same time, teams will anticipate where the ball might be hit in the field and reposition themselves in defensive alignments, called “shifts”, to maximize fielding the ball. Pitchers will throw certain pitches based on these defensive shifts.

The key metric that determines the pitcher/batter competition's success is the ball's launch angle off the bat after it has been hit. Pitchers mainly try to influence the horizontal direction of the ball as it comes off the bat. By controlling this direction, the pitcher controls where in the field the ball will land. If the fielders' defensive shift correctly anticipates the direction the ball is hit, they maximize the batter's chance of being out.

The counter-strategy of the batter is to control the vertical launch angle of the ball. The batter will try to either hit a home run in which case, fielder position does not matter, or hit the ball so sharply that it will thwart the fielders' efforts to get the batter out.

The optimal launch angle is approximately 25 degrees (Sawicki et al., 2003). Figure 4 from Baseball Savant[3] demonstrates the relationship between launch speeds and launch angles. Regardless of the angle, balls hit softly are "weak" contact. Balls hit at too high a launch angle produce easy catches, known as fly-outs or pop-ups. Balls hit at lower launch angles create ground balls, which have lower odds of producing extra-base hits and often create easy outs made by infielders.

Figure 4: Launch Speeds and Launch Angle Relationship, from Baseball Savant.



launch_speed_angle

- Launch speed/angle zone based on launch angle and exit velocity.
  1: Weak
  2: Topped
  3: Under
  4: Flare/Burner
  5: Solid Contact
  6: Barrel

The scheme improves the Astros' offense in two ways. First, the hitters are more selective in what types of pitches they try to hit. If batters know what pitch was coming, they select ones that

[3] https://baseballsavant.mlb.com/csv-docs

they have a higher probability of hitting at the best launch angle. Second, they avoid swinging at non-strike pitches; reducing weak contact and improving the pitch count of the at bat. The number of times a batter swings at a pitch that is not a strike is called the "chase rate."

The audible bang strategy effects the launch speed and angle of balls put in play and benefits of lower chase rates. The results are interpreted in their effects on the offense's total production and runs. The model provides an estimate of the additional wins the Astros gained as a result of cheating.

A fixed-effects panel data methodology is appropriate to estimate the impact of the cheating strategy. The effect on launch speed, launch angle, and chase rate are estimated in Equation (1), Equation (2), and Equation (3). Results are presented in Tables I, II, and III, respectively.

$$\varsigma_{i,g,y} = \beta_A^{\varsigma} A_{i,g,y} + \boldsymbol{\beta}^{\varsigma} \boldsymbol{X}_{i,g,y} + \varepsilon_{i,g,y}^{\varsigma} \tag{1}$$

$$\lambda_{i,g,y} = \beta_A^{\lambda} A_{i,g,y} + \boldsymbol{\beta}^{\lambda} \boldsymbol{X}_{i,g,y} + \varepsilon_{i,g,y}^{\lambda} \tag{2}$$

$$\Pr\left(\mu_{j,i,g,y} = 1 \middle| \boldsymbol{X}\right) = \Phi\left(\beta_A^{\mu} A_{i,g,y} + \boldsymbol{\beta}^{\mu} \boldsymbol{X}_{i,g,y} + \varepsilon_{i,g,y}^{\mu}\right) \tag{3}$$

Equation (1) estimates the effect of the scheme on launch speed per at-bat i during game g denoted as $\varsigma_{i,g}$ only for balls put in play. Equation (2) estimates the effect of the scheme on launch angle per at-bat i during game g denoted as $\lambda_{i,g}$ only for balls put in play. Equation (3) estimates the effect of the scheme on chase rate per pitch j during plate appearance i in game g denoted as $\mu_{j,i,g}$ for all non-strikes faced by the batter. Effective speed of the pitch S, the horizontal movement H, the vertical movement V, fixed effects for pitch type and year, α, were controls common to all estimations as defined in matrix $\boldsymbol{X}$ with vector of coefficients $\boldsymbol{\beta}$.

$$\boldsymbol{\beta}^T \boldsymbol{X}_{i,g,y} = \begin{bmatrix} \beta_0 \\ \alpha_i^p \\ \alpha_{i,g}^y \\ \beta_S \\ \beta_H \\ \beta_V \end{bmatrix}^T \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & S_{i,g,y} & 0 & 0 \\ 0 & 0 & 0 & 0 & H_{i,g,y} & 0 \\ 0 & 0 & 0 & 0 & 0 & V_{i,g,y} \end{bmatrix}.$$

The models uses data from the 2015-2017 MLB seasons.

A is the variable of interest in each equation, indicating the audible signal; the “trashy” hallmark of the Astro’s attempt to alert the batter of the pitch type and potential location. The batter decodes the presence or absence of the signal to learn the kind of pitch he faces next.

When the batter hears the signal, he knows that the next pitch will be the pitcher's primary off-speed pitch. If the batter hears no signal during an at-bat, he knows the pitch would be a fastball with a high probability. All three equations are estimated twice. In the first estimation, *A* takes the binary value of one for all pitches during a plate appearance with the signal present once. In the second estimation, *A* takes the binary value of one only for specific pitches coinciding with the signal. In the tables, the first set of estimations were denoted as **A** while the second set of estimations were denoted **B**.

The results demonstrate that the audible bang resulted in positive and significant increases in launch speeds and launch angles, implying that batters hit the ball better when cheating was occurring.

Table I: Fixed Effects Estimation Results on Launch Speed.

	A		**B**	
	COEFFICIENT	**SE**	**COEFFICIENT**	**SE**
Bang	1.509***	0.672	3.870***	1.052
X Movement	-0.267***	0.028	-0.267***	0.028
Y Movement	-0.933***	0.062	-0932***	0.062
Effective Speed	0.038***	0.007	-0.038***	0.007
Pitch Type FE	x		x	
Year FE	x		x	
Constant	87.199***	0.663	87.199***	0.663

note: *** p<0.01, ** p<0.05, * p<0.1

Table II: Fixed Effects Estimation Results on Launch Angle.

	A		**B**	
	COEFFICIENT	**SE**	**COEFFICIENT**	**SE**
Bang	5.383***	1.072	4.305**	1.694
X Movement	-0.165***	0.045	-0.166***	0.045
Y Movement	11.429***	0.097	11.423***	0.097
Effective Speed	-0.490***	0.012	-0.490***	0.012
Pitch Type FE	x		x	
Year FE	x		x	
Constant	40.324***	1.076	40.325***	1.076

note: *** p<0.01, ** p<0.05, * p<0.1

Table III: Fixed Effects Estimation Results on Swinging at Non-Strikes.

	A		B	
	COEF	**SE**	**COEF**	**SE**
Bang	-0.068*	0.035	-0.298***	0.055
X Movement	-0.002	0.002	-0.002	0.002
Y Movement	-0.109***	0.003	-0.109***	0.003
Effective Speed	0.017***	0.000	0.017***	0.000
Pitch FE	x		x	
Year FE	x		x	
Constant	-2.087***	0.036	-2.088***	0.036

note: *** p<0.01, ** p<0.05, * p<0.1

In both estimations **A** and **B**, the bang signal has a positive association with more potent hits. The correlation is consistent with what one would expect if the cheating is effective. There would be more hits and extra-base hits, such as home runs. Notably, balls hit off pitches the Astros' hitters got the audible signal on are hit particularly hard, 3.87 miles per hour (4.6%) harder than otherwise compared to Statcast data for 2015-2018 for all non-Astros hitters.

Both definitions of "bang" were also associated with increased plate discipline. Astros' players are 2.4% (the calculated marginal effect) less likely to chase non-strikes during plate appearances when the signal is present. Similarly, Astros batters are 9.3% less like to chase specific pitches coinciding with a signal. These results show that the signals improve hitting situations by creating a more favorable ball and strike count. This favorable count leads to getting more pitches that are hittable and walks.

The estimate of additional wins relies on the simple intuition that scoring more runs than the opponent results in winning. Specifically, winning is a function of the difference between the number of runs scored and the number of runs allowed. The principle way that the sabermetric community translates run differentials into an estimated win percentage is the Pythagorean win-loss method.[4] The Pythagorean win-loss method is based on the observation that the relationship between runs scored, runs allowed, and wins is non-linear[5] as Equation (4) shows.

$$Win\ Percentage = \frac{Runs\ Scored^2}{Runs\ Scored^2 + Runs\ Allowed^2} \tag{4}$$

[4] https://www.baseball-reference.com/bullpen/Pythagorean_Theorem_of_Baseball

[5] https://library.fangraphs.com/principles/expected-wins-and-losses

The above estimates measure the increase in offensive production and runs resulting from the cheating scheme. The Pythagorean win-loss formula translates how many additional wins the Astros have due to the extra runs.

Launch speed and angle affect a batter's offensive production in two ways. First, better hit balls improve the probability of reaching base, is measured by the On Base Percentage (OBP)[6]. Second, better hit balls improve the hitting outcomes of batters; it increases the number of hits and converts some hits into more valuable hits. This is tracked by Slugging Percentage (SLG)[7].

Decreasing the batter's chase rate impacts OBP by increasing the number of walks the Astros' batters manage.

The league relationship between launch speed and OBP and SLG, the league relationship between launch angle and OBP and SLG, and the league relationship between the chase rate and OBP are estimated[8] to convert launch and chase rate results into offensive production. This provides the basis for translating the observed point estimates of the three factors into estimates of how cheating increased the Astro's production.

Given these league-wide relationships, each Astros batter's OBP and SLG is corrected for the scheme's estimated benefit. The Astros' batter's OBP and SLG numbers are recalculated from their observed 2017 levels by the weighted number of plate appearances during which bangs are observed[9]. The resulting OBP and SLG numbers are aggregated to the team level. The estimates suggest cheating increased the Astros' team SLG by 5 points and their OBP by 1 point.

The league relationship between OBP and runs, and the relationship between SLG and runs was estimated[10]. These relationships allow for an estimate of the number of runs the Astros should have scored in the absence of the scheme. Table IV presents the observed runs, win percentage, and wins compared to the recalculated runs, win percentage, and wins.

Table IV: Actual and Estimated (Lower Bound) Runs, Win Percentages, and Wins

		Scored	Runs From Scheme	Allowed	Pythag W%	Pythag W	Pythag L
	Actual	896	-	700	62.1%	101	61
SLG	Adjusted	882	14	700	61.4%	99	63
OBP	Adjusted	892	4	700	61.9%	100	62
Total	Adjusted	878	18	700	61.1%	99	63

The Pythagorean results estimate the Astros' cheating scheme earned them 18 runs and won them 2-3 regular-season games they would not have otherwise won.

[6] On Base Percentage (OBP)=(walks+hit by pitches+hits)/plate appearances

[7] Slugging Percentage (SLG)=Total Bases/At Bats or (Singles + Doubles + Triples + Home runs)/At Bats

[8] These estimates are produced in Appendix A

[9] This process is presented in Appendix A

[10] Estimates presented in Appendix A.

These are lower bound estimates as the only audible signal type considered is the banging of the trash can. There is speculation that the team employed other types of audible signals such as whistles, players shouting code words from the dugout, and even buzzers. Further, these estimates only reflect cheating done at home. Teams did have access to live camera feeds when playing at opponent venues. The Astros could have employed the same strategies in stadiums where the typical centerfield camera facilitated seeing the catcher's signals. Thus, estimates accounting for cheating on the road and other signaling forms would yield larger results. Table V presents three upper bound tests assuming the Astros employed the cheating scheme for the entire season, all home games, and all home games after the scheme was employed in full force on May 28th.

Table V: Actual and Estimated (Upper Bound) Runs, Win Percentage and Wins

		Scored	Runs From Scheme	Allowed	Pythag W%	Pythag W	Pythag L
	Actual	896	-	700	62.1%	101	61
Full Season	Adjusted	741	155	700	52.8%	86	76
Home	Adjusted	819	77	700	57.7%	93	69
May 28th	Adjusted	837	59	700	58.8%	95	67

These upper bound tests give a range of 6-15 games potentially won by the scheme.

4. Conclusion

The preliminary results demonstrate a significant and quantifiable effect of the Astros cheating strategy. The Houston Astros developed and implemented an effective signal cheating strategy during the 2017 season that led to better batting outcomes and more wins throughout the season. Given this quantification of the cheating outcome, it is natural to wonder if Major League Baseball should consider further penalties to Astros given their World Series title.

Further development of this project will use more sophisticated methods of estimation, such as nearest-neighbor matching for plate appearance data, and measuring the benefit of the cheating scheme on the performance of individual players, as a cursory evaluation of the data indicates that individual batter outcomes are substantially higher when using the scheme. Nearest neighbor matching could provide fruitful analysis following Dehejia and Wahba (2002). Further the data could provide an empirical application for non-parametric quantile regression methods such as those demonstrated in Atsalakis, Bouri, and Pasiouras (2020) and Wang, Zeng, and Liu (2019).This trashy bang audible signal cheating scheme improved both team level and individual performance for the Astros during the 2017 season, requiring further analysis and deeper consideration than given by Major League Baseball.

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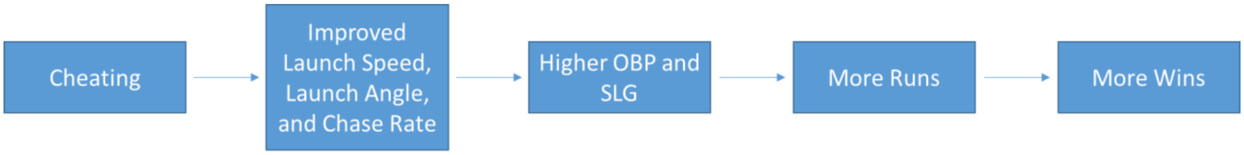
Appendix A

To convert our point estimates of the scheme's impact on players performance into the total impact on the Astros seasons the following three step process is employed. These steps translate the basic benefits of the cheating scheme, those on launch factors and chase rate, into common measurements of player performance, and those into the amount of runs scored by the team, which provides a basis for estimating the number of wins the cheating scheme would have helped the Astros win. Figure 1 presents this process.

1. Convert the point estimates on the Astros' improved launch speed, launch angle, and chase rate into what the expected improvements in OBP and SLG would be via the estimated league wide relationship between these factors.
2. Convert the estimated improvements in OBP and SLG into the expected improvements in runs.
3. Convert the estimated improvement in runs into the expected improvement in wins via the Pythagorean Win formula.

Figure A1. How the cheating scheme impacted the Astros' 2017 season results.



Step 1.

In step one we convert the point estimates of how the Astro's player benefitted from the cheating scheme in terms of launch speed, launch angle, and chase rate into measures of overall offensive performance for players, namely on base percentage and slugging percentage.

To start we estimate the league wide relationship between launch speed, launch angle, and on base percentage following equation A.1. We estimate the league wide relationship between launch speed, launch angle, and slugging percentage following equation A.2. These estimates are presented in Table A.I.

Chase rate impacts on base percentage is two ways. First, it increases the number of walks a batter obtains by not swinging at strikes. Second, it improves the pitch count a batter faces for future pitches which improves his odds to reach base via a hit. Thus, we estimate the league wide relationship between walk rate and chase rate via equation A.3 and between hit rate and chase rate via equation A.4. These estimates are presented in Table A.II.

$$OBP_{f,y} = \beta_0^{OBP} + \beta_1^{OBP}\tilde{\varsigma}_{f,y} + \beta_2^{OBP}\tilde{\lambda}_{f,y} + \ \beta_3^{OBP}\tilde{\lambda}_{f,y}{}^2 + \varepsilon_{f,y}^{OBP} \tag{A.1}$$

$$SLG_{f,y} \ = \beta_0^{SLG} + \beta_1^{SLG}\tilde{\varsigma}_{f,y} + \beta_2^{SLG}\tilde{\lambda}_{f,y} + \ \beta_3^{SLG}\tilde{\lambda}_{f,y}{}^2 + \varepsilon_{f,y}^{SLG} \tag{A.2}$$

$$w_{f,y} = \beta_0^{w} + \beta_1^{w}\mu_{f,y} + \varepsilon_{f,y}^{w} \tag{A.3}$$

$$h_{f,y} = \beta_0^{h} + \beta_1^{h}\mu_{f,y} + \varepsilon_{f,y}^{h} \tag{A.4}$$

Table A.I. Relationship between Launch Speed, and Launch Angle on OBP and SLG in the MLB for 2014-2016

	OBP		**SLG**	
	COEF	**SE**	**COEF**	**SE**
Launch Speed	5.036***	0.075	18.329***	0.151
Launch Angle	2.498***	0.047	6.382***	0.081
Angle Squared	-0.126***	0.001	-0.159***	0.002
Constant	-34.030***	6.848	-1,012***	12.919

note: *** p<0.01, ** p<0.05, * p<0.1

*Scaled OBP is OBP*1000. Scaled SLG is SLG*1000

Table A.II. Relationship between Chase Rate on Scaled OBP and Scaled SLG in the MLB for 2014-2016

	Walk		**Hit**	
	COEF	**SE**	**COEF**	**SE**
Chase Rate	-0.902***	0.008	-0.037***	0.007
Constant	0.579***	0.002	0.334***	0.002

note: *** p<0.01, ** p<0.05, * p<0.1

Given estimates on how improvement in launch speed, launch angle and chase rate translate into improved on base percentage and slugging percentage, we can estimate what each Astro's player's on base percentage and slugging percentage should have been, ie what it would have been in the absence of the cheating scheme. These calculations are presented in equations A.5 and A.6.

$$\widehat{OBP}_\kappa = \widetilde{w}_\kappa NIP_\kappa^{b=1} + w_\kappa NIP_\kappa^{b=0} + OBP_\kappa^{b=0} BIP_\kappa^{b=0} + \left[\frac{BIP_\kappa^{b=1}}{2}\right]\left[\left(\tilde{\varsigma}_\kappa \gamma_1^{OBP} + \tilde{\lambda}_\kappa \gamma_2^{OBP} + \tilde{\lambda}_\kappa{}^2 \gamma_3^{OBP} + \beta_0^{OBP}\right) + \tilde{h}_\kappa\right] \qquad \text{A.5}$$

$$\widehat{SLG}_\kappa = BIP_\kappa^{b=0} SLG_\kappa^{b=0} + BIP_\kappa^{b=1}\left(\tilde{\varsigma}_\kappa \gamma_1^{SLG} + \tilde{\lambda}_\kappa \gamma_2^{SLG} + \tilde{\lambda}_\kappa{}^2 \gamma_3^{SLG} + \beta_0^{SLG}\right) \qquad \text{A.6}$$

Where $\widehat{OBP}_\kappa$ is the estimated On Base Percentage of Astros' cheater κ adjusting for the benefit of the audible signal. $\widetilde{w}_\kappa = (w_\kappa - \overline{w})$ is the corrected Walk Rate for cheater κ. w_k is the observed walk rate when there is an audible signal for cheater κ. $\overline{w}$ is the estimated benefit to the Walk Rate from the Astro's cheating strategy from A.3. $NIP_\kappa^{b=1}$ is the number of Plate Appearances for cheater κ that do no end with a ball in play given an audible signal. $NIP_\kappa^{b=0}$ is the number of Plate Appearances for cheater κ that do not end with a ball in play given no audible signal. $BIP_\kappa^{b=0}$ is the number Balls in Play for cheater κ when no audible signal is observed. $OBP_\kappa^{b=0}$ is the observed On Base Percentage for cheater κ when no audible signals are observed. $BIP_\kappa^{b=1}$ is the number Balls in Play for cheater κ when bangs are observed. $\tilde{\varsigma}_\kappa = (\varsigma_\kappa - \bar{\varsigma})$ is the corrected launch speed of the cheating strategy for Astros cheater κ. ς_κ is the observed launch speed of cheater κ when there is an audible signal. $\bar{\varsigma}$ is the estimated benefit to launch speed from Equation (1). γ_1^{OBP} is the league wide benefit to On Base Percentage from launch speed. $\tilde{\lambda}_\kappa = \left(\lambda_\kappa - \bar{\lambda}\right)$ is the corrected launch angle for cheater κ. λ_κ is the observed launch angle of cheater κ when there is an audible signal. $\bar{\lambda}$ is the estimated benefit to launch angle from Equation (2). γ_2^{OBP} is the league wide benefit to On Base Percentage from launch angle. Similarly, γ_3^{OBP} is the league wide benefit to On Base Percentage from launch angle squared. β_0^{OLG} is a constant from A.1. $\tilde{h}_\kappa = \left(h_\kappa - \bar{h}\right)$ is the corrected Hit Rate for cheater κ. h_k is the observed Hit Rate when there is an audible signal for cheater κ. $\bar{h}$ is the estimated benefit to the Hit Rate from the Astro's cheating strategy from A.4.

For Equation A.6, the Slugging Percentage is dependent on the estimates with similar definitions to the launch speed angle variables. In this case $SLG_\kappa^{b=0}$ is the observed slugging rates for cheater κ when there is no audible signal. In this case then, γ_1^{SLG}, γ_2^{SLG}, and γ_3^{SLG} are the league wide benefits to Slugging Percentage of launch speed, launch angle, and launch angle squared respectively, while β_0^{SLG} is the constant from Equation A.2.

Step 2

Given the corrected On Base Percentage and Slugging Percentages for each Astro player we want to estimate the number of runs the team should have scored in the absence of the scheme. To this end, we first estimate the relationship between runs and On Base Percentage (equation A.7) and Slugging Percentage (A.8) for the entire league. We then use these estimates in conjunction with the corrected On Base Percentages and Slugging Percentages to estimate how many runs the Astros should have scored via equation A.9.

$$R_{f,y} = \beta_0^{R,OBP} + \beta_1^{R,OBP} OBP_{f,y} + \varepsilon_{f,y}^{R,OBP} \qquad \text{A.7}$$

$$R_{f,y} = \beta_0^{R,OBP} + \beta_1^{R,SLG} SLG_{f,y} + \varepsilon_{f,y}^{R,SLG} \qquad \text{A.8}$$

$$R = \beta_1^{R,OBP} \frac{\sum_\kappa \eta_\kappa \widehat{OBP}_\kappa}{\sum_\kappa \eta_\kappa} + \beta_1^{R,SLG} \frac{\sum_\kappa \ell_\kappa \widehat{SLG}_\kappa}{\sum_\kappa \ell_\kappa} \qquad \text{A.9}$$

Where, $R_{f,y}$ is the number of runs scored by team f in season y, $\beta_1^{R,OBP}$ and $\beta_1^{R,SLG}$ are the estimated coefficients from A.7 and A.8. η_κ and ℓ_κ are the plate appearances and at bats of cheater k respectively. Those are weighted by $\widehat{OBP}$ and $\widehat{SLG}$ from A.5 and A.6, and summed over all cheaters.

Table A.III. estimates the marginal impact of On Base Percentage (equation A.7) and Slugging Percentage (A.8) for the league on Runs.

Equation A.9 calculates the numbers of runs the Astros should have scored given the corrected OBP and SLG from equations A.5 and A.6. Notice that the corrected player OBP and SLG results are weighted by the number of plate appearances and at bat the player has.

Table A.III. Relationship between On Base Percentage and Slugging Percentage on Run production in the MLB for 2006-2016.

	A		**B**	
Runs	**COEF**	**SE**	**COEF**	**SE**
Scaled OBP	4.851***	0.149		
Scaled SLG			2.743***	0.069
Constant	-855.689***	48.396	-402.506***	28.455

note: *** p<0.01, ** p<0.05, * p<0.1

*Scaled OBP is OBP*1000, Scaled SLG is SLG*1000.

Step 3.

Given the corrected number of runs, the amount of wins the cheating scheme can was worth can be estimated by the Pythagorean win-loss method. This is presented in the paper.