On the Supply of Autonomous Vehicles in Open Platforms

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MIT Mobility Forum
12/16

Joint work with

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Bikesharing

Analytics and Bikes: Riding tandem with Motivate to Improve Mobility
with Shane G. Henderson, Eoin O'Mahony & David B. Shmoys
INFORMS Journal on Applied Analytics, 2019

Bike Angels: an analysis of Citi Bike's incentives
with Hangil Chung & David B. Shmoys
Proceedings of the 1st ACM SIGCAS Conference on Computing and Computational Sustainability

Minimizing Multimodular Functions and Allocating Capacity in Bike-Sharing Systems
with Shane G. Henderson & David B. Shmoys
Operations Research, 2022

Ridehailing

Pricing Fast and Slow: Inefficicencies of Dynamic Pricing in Ridehailing
with Garrett J. van Ryzin

Pricing and optimization in shared vehicle systems: an approximation framework
with Sid Banerjee & Thodoris Lykouris
Operations Research, 2022

On the supply of AVs in Open Platforms
with Ilan Lobel & Jiayu (Kamessi) Zhao

Driver Positioning and Incentive Budgeting with an Escrow Mechanism for Ride-Sharing Platforms
with Davide Crapis & HaoYi Ong
INFORMS Journal on Applied Analytics, 2021

Today’s talk

Background
Motivation

On the Supply of Autonomous Vehicles in Open Platforms

Takeaways

Underutilization
Curse and promise of AVs

SC misalignment
Consequence of AV underutilization

Contracts
Overcoming misalignments

AV developments

Uber and Motional to launch robotaxis across US over 10 years

Rebecca Bellan @rebeccabellan / 5:00 AM PDT • October 6, 2022

Lyft launches an electric self-driving taxi service in Las Vegas

BY JAMES FARRELL
(HTTPS://SILICONANGLE.COM/AUT

Ride-hailing giant Lyft Inc. and the a
service that will hit the streets of Las

Motional, a $4 billion joint venture be
with Hyundai's Ioniq 5 electric sport
and lidar – that can detect objects fr

"Lyft's powerful network is the ideal
and Chief Executive Logan Green. "
us firmly into the self-driving future."

Uber Eats pilots autonomous delivery with Serve Robotics, Motional

Rebecca Bellan @rebeccabellan / 4:39 PM PDT • May 15, 2022 Comment

The move nods to Uber's strategy, or rather wish, to one day make ride-hail profitable — first by being an "asset-light" company that relies on gig workers driving their own personal vehicles, and now by adding robotaxis to the mix. Uber has said it doesn't intend for AVs to replace drivers and couriers and that it will need a hybrid network well into the future.

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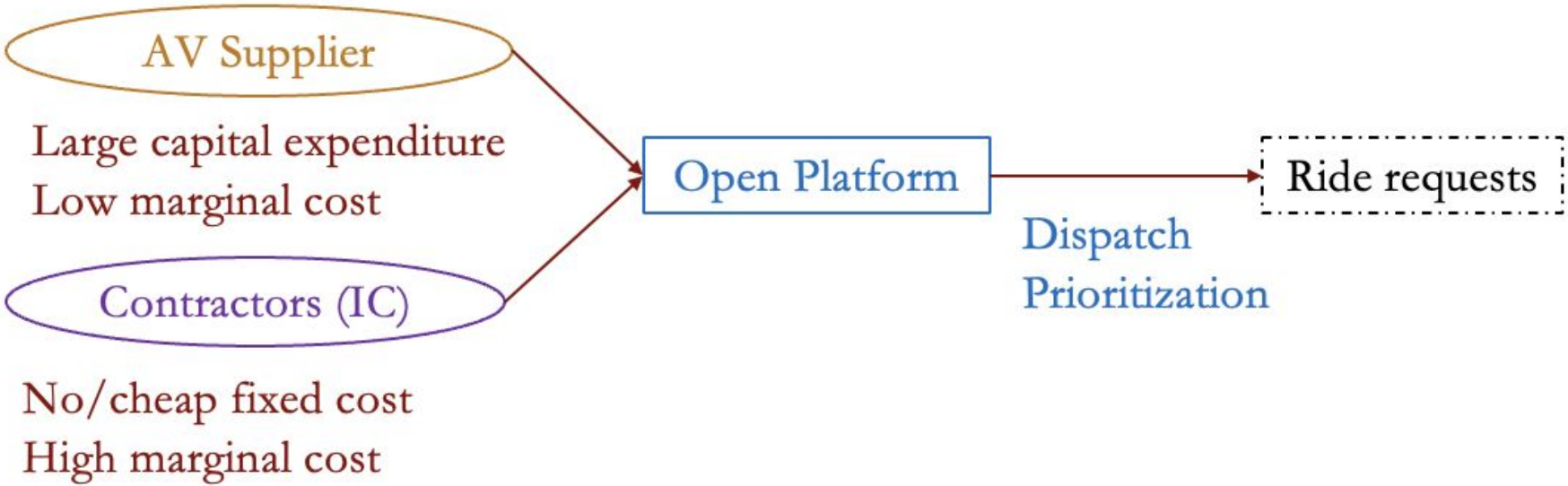
AV Supply Chain

"Waymo has no current plans to sell its modified vehicles to the public and will operate them in an autonomous ride-hailing service instead."

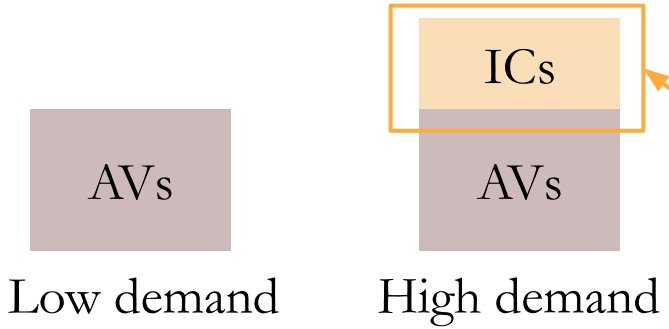
- Waymo CEO John Krafcik

AV Supply Chain



AV Underutilization

Standard dual sourcing solution:



Example

AV fleet size: 20 units
Marginal cost of AVs: $1
Marginal cost of ICs: $15
Reservation earning of ICs: $15
Demand: 20 or 30, each w.p. 1/2

ICs decide to join before demand realizes

❌ Dispatching ICs only when demand is 30 isn't feasible: ICs earn only $15 × ½ < $15

✔️ To meet all demand, platform dispatches 10 units demand to ICs when demand is low

😳 AVs end up idling some of the time despite operating at a very low marginal cost

❌ Endogenizing the marginal cost of ICs would not change this!

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AV mental model

- Open hybrid platforms with both ICs and AVs
  - ICs have high variable cost, no fixed cost;
  - AVs have fixed cost but lower variable cost.

Only-ish setting that makes sense; else, AVs or ICs only!

AV mental model

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  - ICs have high variable cost, no fixed cost;
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Only-ish setting that makes sense; else, AVs or ICs only!

- AVs are owned by outside supplier
- AV supply decisions are made long in advance
- Suppliers have no salvage value for AVs
- Prioritization of fulfillment through either supply type has no cost/limitations

Alternate motivation: *What if AVs can't serve all demand?*

Research questions

- Intuition: can *under-utilization* cause SC misalignment?
- If so, how bad can such misalignment be?
- And is there anything that can be done to overcome it?

Research questions

- Intuition: can *under-utilization* cause SC misalignment?

  Yes!

- If so, how bad can such misalignment be?

  Bad!

- And is there anything that can be done to overcome it?

  Yes!

Model features

- Two types of decisions, two levels of stochasticity:
  - Long-term planning (before 1st level realizes):
    - setting the AV pay per demand served (Platform)
    - setting the AV fleet size (AV supplier)
  - Short-term planning (after 1st level, before 2nd level):
    - determine dispatch prioritization (Platform), which simultaneously incentivizes ICs to join
  - 2nd level stochasticity:
    - Demand realizes, and is served (through AVs and ICs that joint) according to prioritization

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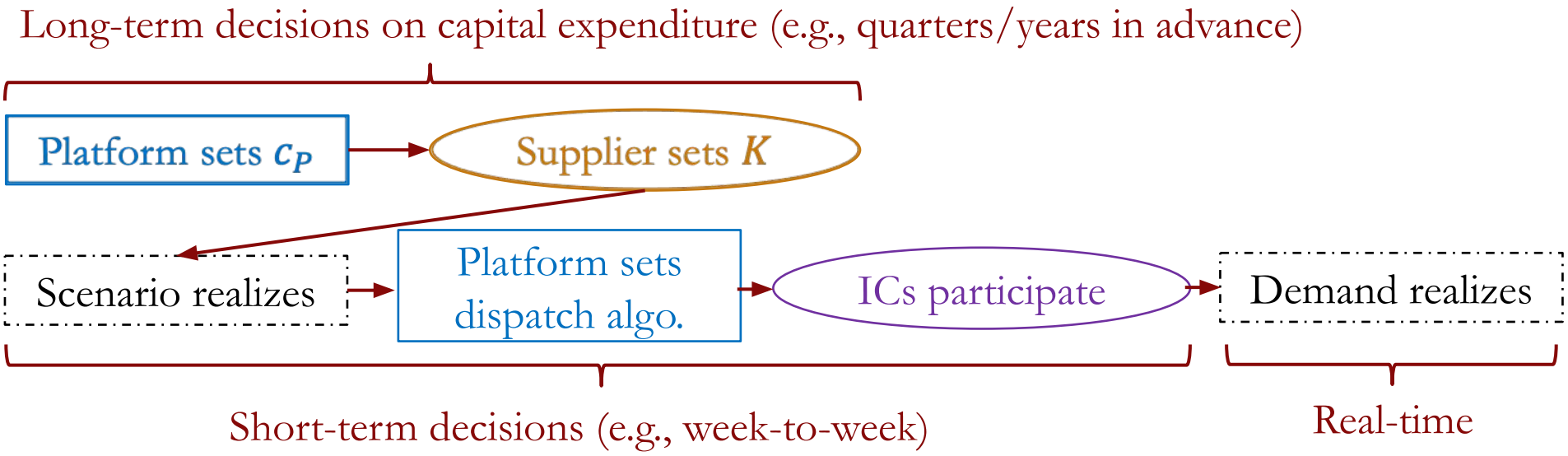
  - 2nd level stochasticity:
    - Demand realizes, and is served (through AVs and ICs that joint) according to prioritization
- Assumptions:
  - No salvage value: once the fleet size is set, if AVs are too idle, there is no recourse
  - No friction: for given realized demand, prioritization between AVs & ICs is unconstrained/free

Formalization: Sequential game



Two levels of stochasticity: Lobel et al. (2021)

Market equilibrium for IC: Hall et al. (2021)

Formalization: Sequential game

The platform will pay the AV supplier c_P *+ marginal cost per ride served.*

Platform decides c_P: unit profit of the supplier

$$\max_{c_P} \sum_i \alpha_i \mathbb{E}_{D_i \sim F_i} \left[(1 - c_{AV} - c_P) \mathcal{A}_i \left(D_i | c_P, K(c_P) \right) + (1 - c_I) \mathcal{H}_i \left(D_i | c_P, K(c_P) \right) \right]$$

AV supplier decides K: AV fleet size

$$\max_K \sum_i \alpha_i \mathbb{E}_{D_i \sim F_i} \left[c_P \mathcal{A}_i \left(D_i | c_P, K \right) \right] - c_F K$$

Platform decides $\mathcal{A}$: AV dispatch, $\mathcal{H}$: IC dispatch

$$\max_{\vec{y}, \mathcal{A}, \mathcal{H}} \sum_i \alpha_i \mathbb{E}_{D_i \sim F_i} \left[(1 - c_{AV} - c_P) \mathcal{A}_i \left(D_i \right) + (1 - c_I) \mathcal{H}_i \left(D_i \right) \right]$$

$$\text{s.t. } 0 \leq \mathcal{A}_i \left(D_i \right) \leq \min \left\{ D_i, K(c_P) \right\}, \forall i$$

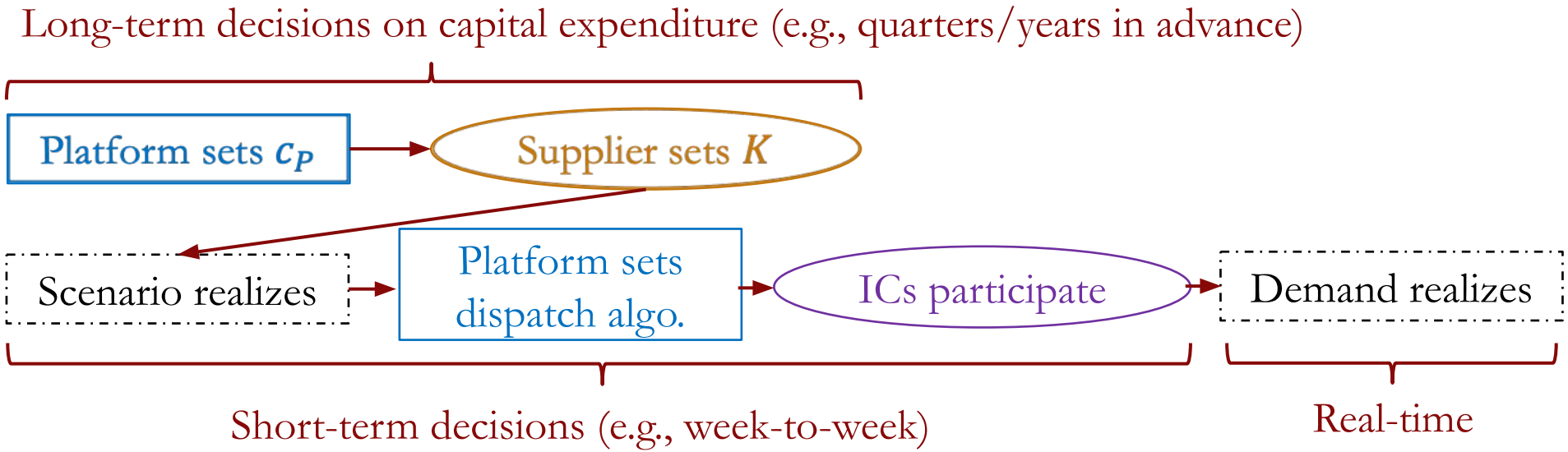
$$0 \leq \mathcal{H}_i \left(D_i \right) \leq \min \left\{ D_i, y_i \right\}, \forall i$$

$$\mathcal{A}_i \left(D_i \right) + \mathcal{H}_i \left(D_i \right) \leq \min \left\{ D_i, K(c_P) + y_i \right\}, \forall i$$

$$t y_i = c_I \mathbb{E}_{D_i \sim F_i} \left[\mathcal{H}_i \left(D_i \right) \right] \ \forall i$$

Quantity of ICs: market equilibrium

Formalization: Sequential game



A solution of the game is a **subgame perfect equilibrium** (SPE), denoted by $\mathbf{s}$

Solve game through backward induction

Platform's dispatch prioritization impacts fleet sizing decision by the AV supplier

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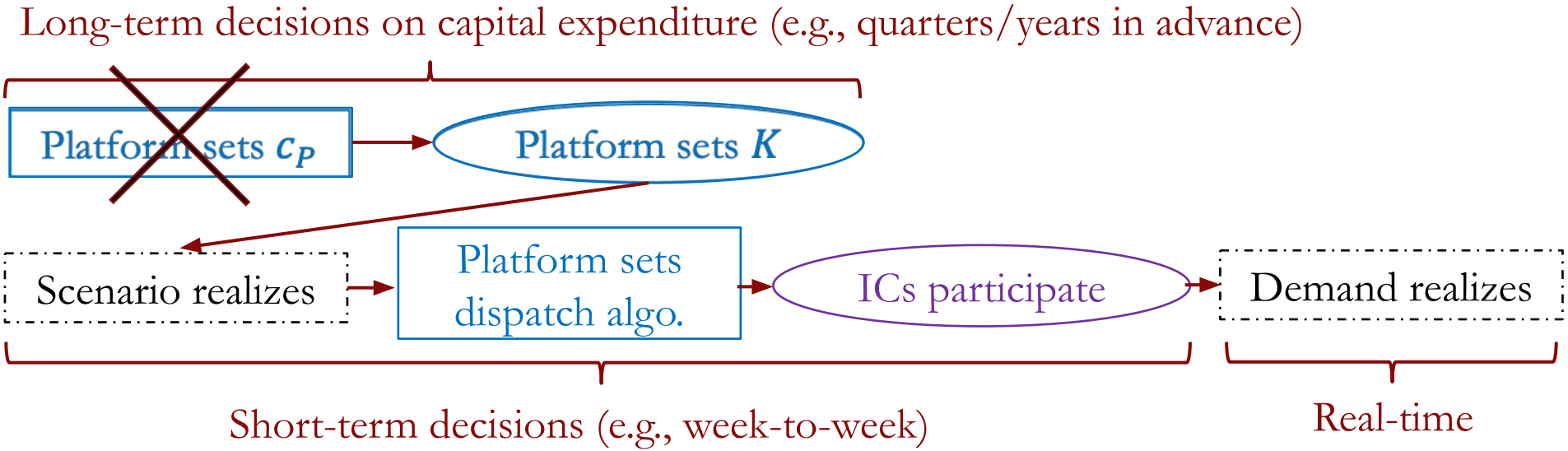
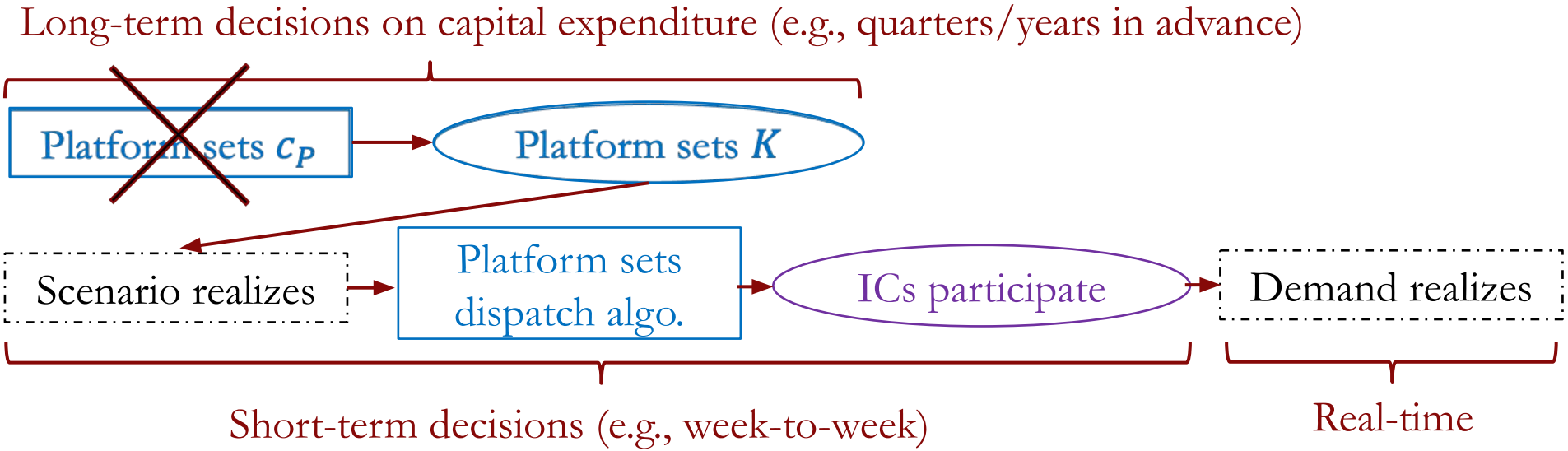
Benchmark: Integration



Benchmark: Integration



Definition

For an instance I, we denote the equilibrium profit and the centralized profit by $V^S(I)$ and $V^*(I)$, respectively. Furthermore, we define **profit ratio**

$$PR^S(I) = V^*(I)/V^S(I).$$

Result #1: Unbounded inefficiency from misalignment

Theorem

For any $M \in \mathbb{R}^+$, there exists an instance I such that for any SPE s we have $PR^s(I) \geq M$.

s: SPE
c_P: unit profit
PR: profit ratio

- A subgame perfect equilibrium may be arbitrarily worse than a centralized solution
- This holds even if AV pay (c_P) is set by a social planner
  - This efficiency loss comes not just from price distortion

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- An equilibrium solution can be arbitrarily worse than a centralized solution
- The above holds even if AVpay is set by a social planner
  - This efficiency loss comes not just from price distortion
- Shown by constructing a family of instances:
  - Optimal solution would use only AVs, no ICs
  - Once AVs are provided, with supplier covering fixed cost, it's platform choose to underutilize AVs
  - AV underutilization incentivizes supplier to not provide any AVs
  - Margins are thin with AVs (but even more so with ICs)

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Result #2: Perfect alignment is possible with…

- Revenue-sharing contract:
  - Widely explored in the supply chain literature
  - But: platforms has to pay the supplier both for rides served by ICs and for rides served by AVs
  - Effectively, supplier needs to become indifferent to dispatch prioritization

Seems unrealistic?

Usage contract

Definition

A **usage contract** π specifies

- c_P^{π}: profit for each unit of demand served by AVs
- K^{π}: AV fleet size
- $\underline{\mathcal{A}}^{\pi}$: platform's minimum AV dispatch

If either player rejects, outcome is a (pre-specified) SPE

c_P: unit profit
K: AV fleet size
$\mathcal{A}$: AV dispatch

s: SPE
PR: profit ratio

Scenarios are contractible: contract may vary minimum AV dispatch policy by scenario

Theorem

For every instance I, there exists a usage contract π that leads to $PR^{\pi}(I) = 1$.

Result #2: Perfect alignment is possible with…

- Revenue-sharing contract:
  - Similar to selling to a newsvendor
  - But: have to pay the supplier both for rides served by ICs and for rides served by AVs
  - Effectively, supplier needs to become indifferent to dispatch prioritization

- A usage contract that contracts on *utilization in each scenario*
  - For every scenario & every demand level, platform commits to how much demand AVs serve
  - Idea: take integrated solution in each scenario & for each demand realization; commit to that level of utilization; share profit in a way that both platform and supplier earn more than in SPE

Seems unrealistic?

Result #3: Perfect alignment is <u>not</u> possible…

- Through usage contracts that are not scenario-dependent

- We can always find situations where the usage pay to the supplier leads the platform to not adopt the integrated solution

Result #4: Approximate alignment is <u>always</u> possible

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- <u>Full prioritization</u> contract:
  - Platform commits to always prioritizing AVs
  - Supplier commits to supply a given number of AVs

Result #4: Approximate alignment is <u>always</u> possible

- <u>Full prioritization</u> contract:
  - Platform commits to always prioritizing AVs
  - Supplier commits to supply a given number of AVs

- Result: Either…
  - … a full prioritization contract achieves **at least half of the profit** that integration achieves, or…
  - … the SPE achieves **at least half of the profit** that integration achieves.

Proof idea:

- <u>Integrated solution:</u>
  - Decompose profit into what is contributed by AVs and what is contributed by ICs
  - Case 1:
    - What is contributed by AVs is at least half of the total
    - Take *optimal* fleet size and full prioritization for AVs
    - Guaranteed to create at least half of the entire integrated SC profit
    - Case 1a: this is less than SPE profit → SPE profit is at least half of integrated SC profit
    - Case 1b: there exists c_P that splits combined profit s.t. both obtain more than in SPE
  - Case 2:
    - What is contributed by AVs is less than half of the total integrated profit
    - Then platform can achieve at least half of that profit by offering c_P=0
    - Platform will achieve at least as much in SPE, so SPE achieves at least as much

Today’s talk

Background
Standard problems in SC contracting

On the Supply of Autonomous Vehicles in Open Platforms

Utilization
SC misalignment in hybrid platform setting due to utilization issue

Contracts
Overcoming misalignments

Takeaways

Numerical results

- Back-of-the-envelope parameter guesses (per ride):
  - Cost of ICs is 60-90% of revenue
  - Cost of AV operation is 10-50% of revenue
  - Fixed cost of AVs is 2.5-40% of revenue (whether idle or not)
- Demand settings:
  - Low: U(10,20)
  - Variance: U(10,40)
  - High: U(30,40)

Summary statistics

- Misalignment can indeed be significant in plausible instances!
  - Up to 25.9%
  - Mean misalignment of 6.5%
  - At least 14% in a tenth of the cases
- Full prioritization contracts mostly overcome the misalignment

Summary statistics

- Misalignment can indeed be significant in plausible instances!
  - Up to 25.9%
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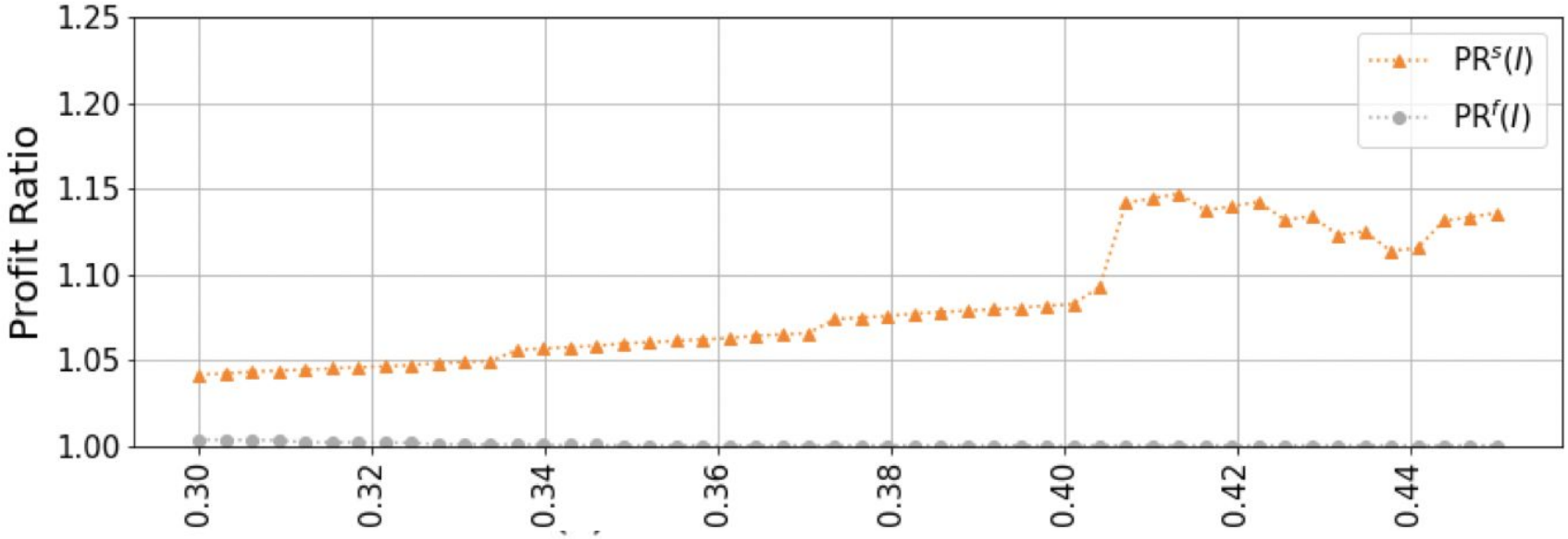
- Full prioritization contracts mostly overcome the misalignment

$\mathrm{PR}^s(I)$				$\mathrm{PR}^f(I)$				$\mathrm{PR}^\pi(I)$			
Mean	Median	90th PR	Max	Mean	Median	90th PR	Max	Mean	Median	90th PR	Max
1.065	1.049	1.140	1.259	1.002	1.000	1.005	1.036	1.001	1.000	1.005	1.031

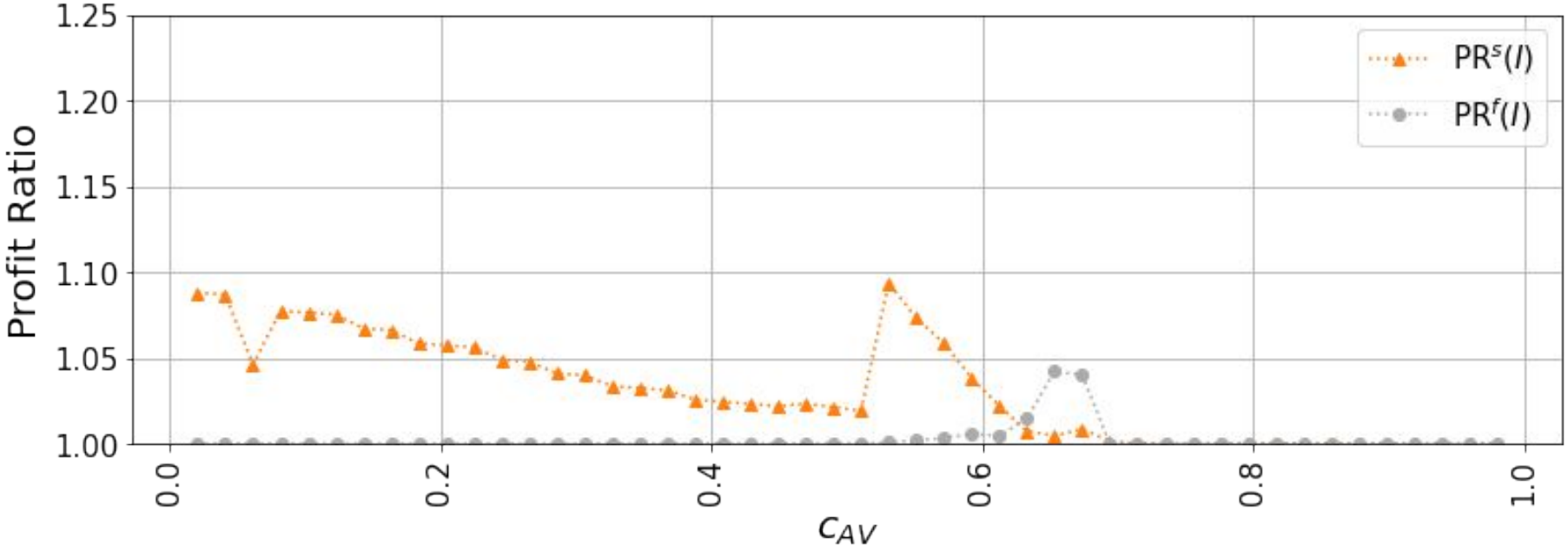
Table 1 **Summary statistics of supply chain outcomes across the extensive experiments in Appendix**

When is misalignment significant? Thin margins



Example where c_I, c_{AV} and c_F proportionately scale up.

Spirit of 2-approximation result



Takeaways

- “*We don‘t prioritize”* is a prioritization strategy & it may not be a good one

- Prioritizing AVs seems natural; may collapse IC market; may be suboptimal

- AVs are likely to introduce SC contracting into platform operations

Conclusion

- Speculative setting of AV future
- Hybrid platform with surprising source of misalignment (AV Underutilization)
- Theoretical worst-case outcome
- Opportunity of SC design for autonomous technologies on platforms
  - Unconvential designs (utilization-based)
  - Practically feasible?

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https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4178508

Questions?

Thank you!

Implications/Discussion

- Is this a real concern (not today, but tomorrow)?
  - Strengths: partial characterization of SC challenges for AV platform adoption
  - Shortcomings: too stylized to justify specific actions!
  - How can we know today whether this will be an issue tomorrow?

- What kind of contracts are feasible in practice?