Design of cyberphysical autonomous mobility platforms

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Workshop III: Large Scale Autonomy: Connectivity and Mobility Networks
The transportation field has changed significantly

1950s-60s

Last 5 years


https://www.bart.gov/about/history/history2
Trend 1: Mobility-as-a-Service (MaaS)

“MaaS combines transport services from public and private transport providers through a unified gateway that creates and manages the trip, which users can pay for with a single account.” – Hensher (2017)

Trend 2: SAV fleets

Testing of First Autonomous Shuttle on Public Roads in California Begins


CA DMV grants permission for shared autonomous vehicle testing at Bishop Ranch

The first 100 of Baidu's "Level 4" self-driving buses have rolled off the production lines, said Robin Li, chief executive of China's largest search engine operator on Wednesday.

The self-driving buses, which can seat up to 14 people, were co-developed by Baidu, which is transforming itself into an artificial intelligence (AI) company, and bus maker King Long United Automotive Industry Co. Level 4 operations means that the vehicles can take over all driving in certain conditions.

With no steering wheel and high automation, the buses will be put into use in cities including Beijing, Xiongan, Shenzhen and Tokyo, Li said at the Baidu AI Developer forum being held in Beijing. "They will help with shuttle services around nuclear power stations and senior communities in Japan," for example, said Li. Baidu will partner with SB Drive, a subsidiary of SoftBank Group, to export the self-driving buses to Japan.

https://www.scmp.com/tech/article/2153694/baidu-says-first-100-self-driving-buses-have-rolled-production-lines

Research questions

• How to evaluate the stability of an ecosystem of mobility providers?
  • If a new service enters the market? If a service improves its technology?

• How can public agencies facilitate these ecosystems?
  • Comparing between different interventions: infrastructure investments, subsidies, taxes, regulating toward social optimum

• How might automation affect these systems?
Outline

1. Platform economics for MaaS markets
2. Market evaluation of cyberphysical platforms
   a) Model
   b) A scalable algorithm
   c) Numerical examples
   d) Evidence of methodology with Luxembourg microtransit service
3. Impacts of automation
Platform economics for MaaS markets
“Multi-sided markets are markets in which one or several platforms enable interactions between en-users and try to get the two (or more) sides ‘on board’ by appropriately charging each side.” – Rochet and Tirole, 2006
Cities are multisided cyberphysical platforms
(Chow, 2018)

- The two sets of end users are the **Travelers** (buyers) and the mobility **Operators** (sellers)
- Platforms may interface **physically** (built environment) or **digitally** (travel apps, e-commerce)
- Cities’ “platform pricing” take several forms:
  - **Built environment** affects travel costs
  - **Taxes/subsidies** further augment costs to operators/travelers
  - **Regulations** define the pricing structures

There is a need to model such systems as platforms.

<table>
<thead>
<tr>
<th>Use case</th>
<th>Model parameters</th>
<th>Required model output</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Technology</strong>: evaluate/regulate market due to new algorithm or operating policy from an operator <strong>Subsidy</strong>: platform may subsidize one or more of the operators</td>
<td>Changes to travel disutilities of travelers (which may be in-vehicle, access, or wait time), link operating costs, or link capacities of operators Change in threshold for an operator to leave a market (they might be able to operate at a loss up to a threshold); cost allocation for that operator may align with welfare maximizing instead of profit maximizing</td>
<td>Impact on operator routes that stay in market, passenger link flows, and how their stable price range changes Links that can be operated in this setting, revenues and flows under the changed setting</td>
</tr>
<tr>
<td>Tax: platform may impose a surcharge on a subset of operators <strong>Merger</strong>: two or more operators in a platform may merge or ally <strong>Investment</strong>: evaluate/regulate market due to increased investment by an operator on their fleet size, new service coverage area, etc. <strong>Disruption</strong>: links may be closed or degraded</td>
<td>Changes to operating cost for the operators The stability conditions would treat those operators as a single operator New candidate links/nodes in network, changes to link capacities</td>
<td>Changes in operating links, flows, and shifts in stable pricing range as a result of surcharge Changes in revenue and ridership due to the merger Whether those links stay in the market, subsequent flows, prices for new services as well as impacts on other operators</td>
</tr>
</tbody>
</table>
Market evaluation of cyberphysical platforms


How to evaluate platforms that operate with multiple operators?

- Assignment of travelers to a MaaS network is not just determining flows that make sense to them, but also making sense to operators (which links to operate, what price* to charge)
- Blue owns (1,3) and (1,21) – serving (1,3) would compete with Orange for OD (1,3), but Orange can also cooperate with Blue through path (1,21,22,3), and (1,21) can also benefit Green
- The system also exhibits flow capacities that affect the route choices of travelers
- Each link is owned by at most one operator

*price assumed to be a fixed charge to users to access that operator any number of times per trip
Assumptions

Travel utility is transferable between travelers and operators:
- Transit operators’ performance includes traveler disutilities like wait time
- Shared rides (detours) for discounts
- Increased access time to “virtual stops” for discounts
- Transfers/layovers for discounts

Operators charge single access, constant fares per traveler-path
If utility is transferable, we can model the MaaS platform market as an assignment game

- In a one-to-one assignment game (Shapley and Shubik, 1971):
  - Set of buyers $P$ and set of sellers $Q$ are matched together which generates utility $U_{ij}$ for each pairing of buyer $i \in P$ to seller $j \in Q$ at a cost of $c_j$
  - The optimum matching $x_{ij}$ between the two sets is found using a matching subproblem to maximize payoffs $a_{ij} = \max(0, U_{ij} - c_j)$
  - Given that optimal matching, a stable outcome subproblem determines the cost allocations $p$ set between seller and buyer that satisfy the incentives of buyers ($u_i = U_{ij} - p$) and sellers ($v_j = p - c_j$)
  - There can be multiple stable cost allocations: a stable mechanism that maximizes $u_i$ is “buyer-optimal”, one that maximizes $v_j$ is “seller-optimal”
  - An optimal matching that has an empty stable outcome space is not sustainable

One-to-one assignment game

Matching subproblem

\[
\max \sum_{i \in P} \sum_{j \in Q} a_{ij} x_{ij}
\]

s.t.

\[
\sum_{i \in P} x_{ij} \leq 1, \quad \forall j \in Q
\]

\[
\sum_{j \in Q} x_{ij} \leq 1, \quad \forall i \in P
\]

\[
x_{ij} \in \{0, 1\}, \quad \forall j \in Q, i \in P
\]

Constraints of stable outcome subproblem

(/objective depends on cost allocation mechanism)

\[
u_i + v_j \geq a_{ij}, \quad \forall i \in P, j \in Q
\]

\[
\sum_{i \in P} u_i + \sum_{j \in Q} v_j = \sum_{i \in P} \sum_{j \in Q} a_{ij} x_{ij}
\]

\[
u_i, v_j \geq 0
\]
Challenges to overcome for MaaS platforms

• Many-to-many assignment game: multiple operators serve multimodal trip, multiple travelers share a ride
• Link capacities lead to network effects that need to be captured by stable outcome subproblem
• Matching subproblem is a multicommodity capacitated network design problem
Some notation

Parameters
• $t_{ij}$: disutility experienced on link $(i, j)$ on a directed graph $G(N, A)$
• $c_{ij}$: operating cost of link $(i, j)$
• $d_s$: demand of user group $s \in S$
• $w_{ij}$: flow capacity of link $(i, j)$

Decision variables
• $x_{ij}^s$: flow of user group $s \in S$ on link $(i, j)$
• $y_{ij}$: binary variable for whether a link is operated
• $p_{rf}$: price charged by operator $f \in F$ to travelers $s \in S$ on path $r \in R_s^*$
• $z_r$: the flow on path $r \in R_f$ served by operator $f \in F$
Assignment game model for MaaS market

Matching subproblem (link variables)

\[
\min Z = \sum_{(i,j) \in A} \sum_{s \in S} t_{ij} x_{ij}^s + \sum_{(i,j) \in A} c_{ij} y_{ij}
\]

\[
\sum_{j \in N_i(\pm)} x_{ij}^s - \sum_{j \in N_i(\pm)} x_{ji}^s = \begin{cases} 
-d_s, & i = O(s) \\
0, & i = D(s), \forall i \in N, s \in S
\end{cases}
\]

\[
\sum_{s \in S} x_{ij}^s \leq w_{ij} y_{ij}, \quad \forall (i,j) \in A
\]

\[
x_{ij}^s \geq 0, \quad \forall (i,j) \in A, s \in S
\]

\[
y_{ij} \in \{0,1\}, \quad \forall (i,j) \in A
\]

Stable outcome subproblem (path variables)

\[
u_s + \sum_{f \in R_r} p_{rf} = U_s - \sum_{(i,j) \in A_r} t_{ij}, \quad \forall r \in R_s, s \in S
\]

\[
u_s \geq 0, \quad \forall s \in S
\]

\[
p_{rf} \geq 0, \quad \forall r \in R, f \in F
\]

\[
\sum_{r \in R_f} p_{rf} z_{rf}^* \geq \sum_{(i,j) \in A_f} c_{ij} y_{ij}^*, \quad \forall f \in F
\]

Does this mean we need to enumerate alternate paths?
Although paths are non-unique,

- Link flows and total path costs are unique ➔
  - Revenues gained by operators and total consumer surplus are unique
  - A unique stable outcome space for a given matching, but cannot guarantee the opposite
- Model can be used for *ex post* evaluation to quantify changes in a market
Model can be used to analyze stylized examples

In case (a), Orange would collaborate with Blue only if its price $p_o$ can be charged higher than:

$$p_o \geq \frac{c_{12} + c_{23}}{d} - t_{13} - c_{13} + t_{12} + t_{23}, \text{ if } t_{12}d + t_{23}d + c_{12} + c_{23} \leq t_{13}d + c_{13}$$

In case (b), Orange would enter the market as shown only if its price doesn’t exceed the following:

$$p_{2o} \leq \begin{cases} t_{23}^b - t_{23}^o + c_{23}^b, & \text{if } x_{23}^b = 0 \\ 0, & \text{if } x_{23}^b > 0 \end{cases}$$
Algorithm to generate constraints without explicit path enumeration

\[ \Pi(F_{R_s^*}) \] is a set of permutations of coalitions of operators drawn from the route being considered, i.e. if there are 3 operators on a route, it would iterative check the removal of \({\{1\}, \{2\}, \{3\}, \{1,2\}, \{1,3\}, \{2,3\}, \{1,2,3\}}\)
Numerical test

Example network with 6 nodes, 6 operators, and 2 OD pairs assigned to 6 paths.
Example: Sioux Falls

Firm entry

<table>
<thead>
<tr>
<th>Parameters: Scenarios</th>
<th>Revenues ($) [(f = 1, 2, 3)]</th>
<th>Avg. operator fare ($) [(f = 1, 2, 3)]</th>
<th>Avg. operated link revenue ($)</th>
<th>Operator ridership (\sum x_{f}) [(f = 1, 2, 3)]</th>
<th>Runtime: Model generation / Solution (msec) (original IP)</th>
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Algorithm can scale up

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<td>(6, 106)*</td>
<td>9600</td>
<td>(10, 11)</td>
<td>18500</td>
</tr>
</tbody>
</table>

Links with * represent operator transfers

<table>
<thead>
<tr>
<th>Operator</th>
<th>Revenue ($)</th>
<th>Avg fare ($)</th>
<th>Min fare ($)</th>
<th>Max fare ($)</th>
<th>Passengers</th>
<th>Operating costs ($)</th>
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</thead>
<tbody>
<tr>
<td>Bus Service (1)</td>
<td>6,509,832</td>
<td>23.68</td>
<td>1.00</td>
<td>38.00</td>
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<td>1.00</td>
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</table>

Pricing and ridership breakdown by operator.
Insights

• Proposed algorithm can take 17 sec to solve Sioux Falls example that would require more than 2 hrs with explicit path enumeration

• The base scenario assumes seller-optimal for both. Government rail acquisition intervention changes the objective to buyer-optimal but the savings end up going to private operator, not the users, due to shared trips

• Addition of a new competitor can result in significant advantages to a third party; Operator 1 benefited greatly by being able to increase its price because a new Operator 3 entered to compete with Operator 2

• Capacity increases even for single links have nonlinear effects: exceeding a threshold improvement can lead to a significant shift in assignment and stable outcomes, which can also impact revenues of other operators
Significance/next steps

• The assignment game method has been applied to the Kussbus microtransit service in Luxembourg and correctly predicted its failure

• Currently advising NY State DOT on procuring the next statewide mobility services program

• Next research objectives:
  • Integrate congestible capacity route choice SUE into the assignment game
  • Consider assignment game from a multimodal activity-scheduling context

Stable outcome space for the Kussbus service, which ended up closing down later
Impacts of automation
AVs can add optimal learning into fleet operations.

Figure 5. Regret measures of shortest path algorithm and on-time UCB algorithm.

Figure 6. The top three paths considered in the sequential route selection experiment.

Table 3. Numerical Results after Running the Three Scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>SP on-time arrivals</th>
<th>On-time UCB on-time arrivals</th>
<th>SP mean rewards</th>
<th>On-time UCB mean rewards</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>47%</td>
<td>75%</td>
<td>0.0347</td>
<td>0.0394</td>
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<tr>
<td>2</td>
<td>87%</td>
<td>91%</td>
<td>0.0325</td>
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<td>3</td>
<td>70%</td>
<td>77%</td>
<td>0.0305</td>
<td>0.0320</td>
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</tbody>
</table>

Note: SP = shortest path; UCB = upper confidence bound.
Optimal learning applied to SAV-based line planning as well

Line planning done sequentially with optimal learning can approach oracle line planning solution quality

AVs’ ownership can be shared between owners (like time-share plans)

• AVs can self-valet, so new fractional ownership business models can be added to the MaaS market

• Time of day prices can be derived from users’ activity scheduling behavior

Modular autonomous vehicles are feasible

- Dispatch can be more dynamic using stochastic optimization
- Shifts of transfers from stations to in-vehicle can reduce travel distance and wait time by 18-19% for Dubai-Sharjah corridor


Conclusion

• MaaS markets need to be evaluated as cyberphysical platforms
• Design of such platforms can be evaluated using many-to-many assignment games
• Our approach can be applied to realistic networks to derive important insights
• It has been applied to Kussbus microtransit in Luxembourg and successfully predicted its instability
• Automation can further improve MaaS markets: optimal learning, new business models using self-valet, and modularity without drivers
Acknowledgments/Contact Info

• Email: joseph.chow@nyu.edu, or on Linkedin

• Key researchers whose work I presented
  • Students: Saeid Rasulkhani, Ted Pantelidis, Jinkai Zhou, Gyugeun Yoon, Nick Caros, Ziyi Ma, Xuebo Lai
  • Collaborators: Tai-yu Ma, Sylvain Klein (LISER); Mahdieh Allahviranloo (CCNY); Qianwen Guo (FSU); Paul Schonfeld (UMD)

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