Strategies for Operating a Fleet of Autonomous Vehicles to Provide Passenger Transportation Service

Michael Hyland and Hani Mahmassani
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Transport Chicago
Motivation

- Fully-autonomous vehicles (AVs) expected to accelerate existing trends toward shared urban mobility
- AVs eliminate cost and performance limitations associated with human drivers
  - Allow mobility services to compete with personal vehicles in terms:
    - Cost
    - Quality of service (i.e. short wait times)
- Other technological advancements leading toward immediate and reliable communications of instructions to AVs and travelers
- Existing and future shared urban mobility services expected to fill gaps between traditional public transit and personal mobility
- Expect a wide-variety of AV fleet business models
Conceptual Model of AV Fleet Business

• Similar to Ridesourcing companies like Uber and Lyft except cars are **driverless**
  • Also, fleet operator has complete control over each AV in the fleet

• AV Fleet provides **Urban, Passenger** Transportation Service

• AV Fleet competes with individual car ownership, in terms of:
  • Cost
  • Quality of Service

http://www.dailymail.co.uk/news/article-3444495/Omaha-woman-gets-restraining-order-against-Uber-driver.html
AV Fleet Business Models for Mobility Service

Potential Variants

AV Fleet Business Model Decisions

Strategic Decisions

Pricing
- Variance (e.g., Material Cost)
  - Fixed
- Reservation Time-frame
  - Advanced Requests
  - Immediate Requests
- Shared Rides
  - Sharing
  - No Sharing
- Reservation Type
  - Point-to-Point
  - Hourly
- Vehicles
  - Heterogeneous
  - Homogeneous
- Fleet Size Elasticity
  - Variable/Elastic
  - Fixed
- Vehicle Fuel-Type
  - Electric
  - Conventional Gasoline

Tactical Decisions

Vehicle Repositioning

Diverting En-route Vehicles

Request Hold before Assignment
1. **Develop an agent-based simulation tool** to model the movements and behavior of:
   - Travelers
   - AVs
   - AV fleet operator

2. **Develop optimization-based strategies** to efficiently **operate an AV fleet**
   - Assign travelers to AVs
   - Route and schedule AVs to pick-up and drop-off travelers
   - Minimize operational costs
   - Maximize customer quality-of-service (i.e. minimize wait time and in-vehicle travel time)

3. **Implement and test the operational strategies in the agent-based simulation environment**
Dynamic AV Fleet Management Problem Overview

- **3 Possible AV States**
  - Idle
  - En-route to pick-up traveler
  - En-route to drop-off traveler

- **4 Possible Traveler States**
  - Unassigned
  - Assigned
  - In-Vehicle
  - Served
Dynamic AV Fleet Management Problem Overview

• Travelers request rides via a smart-phone
  • Request info: Origin and Destination
  • Assumption: travelers want to be served immediately

• New requests need to be assigned to an AV
  • AVs may currently be idle or busy

• The AV fleet controller needs to decide what AVs to assign to the traveler requests
  • AV fleet operator has complete control over all the AVs
  • In this research, we examine various AV-traveler assignment strategies
AV-Traveler Assignment Strategies

Simplistic Strategies

• **Strategy 1**: Travelers are served first-come, first served (FCFS) by longest idle AV
  • Similar to original taxi-dispatching strategies

• **Strategy 2**: Travelers are served FCFS, but assigned to nearest idle AV
  • This is a slightly less myopic/greedy strategy
AV-Traveler Assignment Strategies

Optimization-based Strategies

• **Strategy 3**: Assign travelers to idle AVs, such that the total wait time across the travelers is minimized

• **Strategy 4**: The same as Strategy 3, except AVs in en-route pick-up state can be reassigned
  - Shown to be highly-beneficial in the context of truckload freight transportation

• **Strategy 5**: The same as Strategy 3, except AVs in en-route drop-off state are included in matching
  - Least myopic/greedy strategy. Takes advantage of knowledge of AVs future locations

• **Strategy 6**: Shared-rides
  - All the previous strategies assigned one traveler to one AV
Simulation Parameters

Fixed

• 2.5 mile x 2.5 mile grid
  • Approximately, the area of Evanston, IL
• 2 hour simulation period
• AV Speed: 20mph
• AV Capacity: 5 persons
• Demand rate: 1500 travelers/hour = 25 travelers per minute
• Traveler origins and destinations: Uniformly distributed
• Pick-up and Drop-off Time: 0 seconds
• Network
  • Manhattan and Euclidean Network ← Not a real road network
  • Deterministic Travel Times ← No congestion and no stochasticity
Simulation Parameters

**Variable**

- **Fleet Size**: 160 AVs – 230 AVs \(\leftarrow\) Increments of 10
- **Hold time before assigning travelers and AVs**: 1 sec. – 30 sec.
  - A longer hold time allows traveler requests and AVs to form a queue
    - Advantage: Better matching between travelers and AVs
    - Disadvantage: Longer wait time before assigned, and possible longer wait time before being picked up
Simulation Platform and Optimization Solver

- **Python 2.7.8**
  - Objected-oriented programming language

- **Gurobi 7.0.2**
  - Optimization Solver embedded in Python
  - Formulate integer problem in Python and use Gurobi library to call solver
Takeaway 1

Strategy 1 is Very Inefficient

• Reminder of Strategy 1
  • Travelers: First Come, First Served
  • AVs: Longest Idle AV

• Fleet Size of 180 AVs
  • Strategy 1: 350/3,000 (>10%) unserved travelers
  • Strategy 2: 10/3,000 unserved travelers
  • Strategies 3-6: 0 unserved travelers

• Fleet Size of 230 AVs
  • Strategy 1: Average Pickup Time ~= 10 minutes
  • Strategies 2-6: Average Pickup Time ~= 1 minutes
Takeaway 1
Strategy 1 is Very Inefficient

Average Wait Time before Traveler Assigned

- Trav. - FCFS
  - Veh. - Longest Idle
- Trav. - FCFS
  - Veh. - Nearest Idle
- Best Match
  - Idle Vehicles Only
- Best Match
  - Idle and En-route Pickup Vehicles

Strategy 1
Takeaway 2

Optimization-based Strategies outperform FCFS

• Reminder of Strategy 2 ← a FCFS AV assignment strategy
  • Travelers: First Come, First Served
  • AVs: Nearest Idle AV

• Fleet Size of 160 AVs
  • Strategy 2: 200/3,000 (>5%) unserved travelers
  • Strategies 3-6: 0 unserved travelers
    • Strategies 3-6 are optimization-based ← min cost assignment

• Fleet Size of 190 AVs
  • Strategy 2: Average Pickup Time ~= 3-7 minutes
  • Strategies 3-6: Average Pickup Time ~= 1 minutes
Takeaway 2
Optimization-based Strategies outperform FCFS

Average Wait Time Before Traveler Assigned

- Orange line: Trav. - FCFS
- Yellow line: Best Match Idle and En-route Pickup Vehicles
- Gray line: Best Match Idle Vehicles Only
- Blue line: Best Match Idle and En-route Drop-off Vehicles

Strategy 2: FCFS

Optimization-base Assignment Strategies
Takeaway 2
Optimization-based Strategies outperform FCFS

Strategy 2: FCFS

Optimization-base Assignment Strategies
Takeaway 3

Beneficial to include En-route Pick-up AV Diversions

• Strategy 3: Best Traveler – **Idle** AV Assignment
• Strategy 4: Best Traveler – **Idle & En-route Pick-up** AV Assignment
  • AVs that are en-route to pick-up a traveler can be reassigned to another traveler ← beneficial with dynamic requests entering system
Takeaway 3
Beneficial to include En-route Pick-up AV Diversions

Average Wait Time Before Assignment

- Best Match Idle Vehicles Only
- Best Match Idle and En-route Pickup Vehicles

Strategy 4: Diversions
Takeaway 3

Beneficial to include En-route Pick-up AV Diversions

<table>
<thead>
<tr>
<th>Fleet Size</th>
<th>Fleet Miles</th>
</tr>
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<tbody>
<tr>
<td>160</td>
<td>5,000</td>
</tr>
<tr>
<td>170</td>
<td>5,500</td>
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<tr>
<td>180</td>
<td>6,000</td>
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<tr>
<td>190</td>
<td>6,500</td>
</tr>
<tr>
<td>200</td>
<td>7,000</td>
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Strategy 4: Diversions
Takeaway 4

Beneficial to include En-route Drop-off AVs in Assignment

• Strategy 3: Best Traveler – **Idle** AV Assignment

• Strategy 4: Best Traveler – **Idle & En-route Pick-up** AV Assignment
  • AVs that are en-route to pick-up a traveler can be reassigned to another traveler ←
    beneficial with dynamic requests entering system

• Strategy 5: Best Traveler – **Idle & En-route Drop-off** AV Assignment
  • If AV currently dropping off a traveler can get to new request fastest, this en-route
    drop-off AV is assigned to traveler request
Takeaway 4
Beneficial to include En-route Drop-off AVs in Assignment

Strategy 5: Include En-route Drop-off AVs in Assignment
Takeaway 4

Beneficial to include En-route Drop-off AVs in Assignment

Strategy 5: Include En-route Drop-off AVs in Assignment
Shared-Rides
Takeaway 5

Shared-Rides **reduce Fleet Miles** and Traveler Wait Time with small increase in Traveler IVTT

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<td>170</td>
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<tr>
<td>180</td>
<td>5,800</td>
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<td>190</td>
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<td>200</td>
<td>5,400</td>
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<tr>
<td>210</td>
<td>5,200</td>
</tr>
<tr>
<td>220</td>
<td>5,000</td>
</tr>
<tr>
<td>230</td>
<td>4,800</td>
</tr>
</tbody>
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**Fleet Size**

- **Idle and En-route Pickup**
- **Idle and En-route Drop-off**
- **Rideshare**

**Strategy 6: Shared-Rides Allowed**
Takeaway 5

Shared-Rides **reduce** Fleet Miles and **Traveler Wait Time** with small increase in Traveler IVTT

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**Strategy 6: Shared-Rides Allowed**
Takeaway 5

Shared-Rides reduce Fleet Miles and Traveler Wait Time with *small increase in Traveler IVTT*

Strategy 6: Shared-Rides Allowed
Summary and Conclusion

• Developed **agent-based simulation tool** to model the movements and behavior of:
  • Travelers
  • AVs
  • An AV fleet operator

• **Developed strategies** to efficiently **operate an AV fleet**
  • Optimization-base strategies outperform FCFS rules
  • Including non-idle AVs in assignment improves efficiency
  • Given a fixed fleet size, shared rides improve operational efficiency and customer quality-of-service
Thank you very much!

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Extra Slides

Mathematical Formulation of AV-Traveler Assignment Problem
Highly-Dynamic, Multi-Vehicle Passenger Pickup and Delivery Problem with Immediate Demand Requests

• Travelers request rides dynamically, and want to be served immediately
  • Request time = Earliest pickup time
  • Operator has no knowledge of demands prior to request time

• A central operator has complete control over an AV fleet

• Central operator assigns AVs to pickup and drop-off traveler requests
  • In this presentation, we examine various optimization-based AV-traveler assignment strategies

• Objective is to minimize combination of operational costs (i.e. AV fleet miles) and traveler quality-of-service (i.e. wait time)
## Problem Definition

### Taxonomic Classification

<table>
<thead>
<tr>
<th>AVs</th>
<th>Travelers</th>
<th>Information</th>
<th>Network</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-vehicle</td>
<td>Pickup and Drop-off</td>
<td>Dynamic</td>
<td>Manhattan</td>
</tr>
<tr>
<td>Fixed Fleet Size</td>
<td>Immediate Requests</td>
<td>Stochastic</td>
<td>Deterministic Travel Times</td>
</tr>
<tr>
<td>Homogenous</td>
<td>Must be served</td>
<td>Global</td>
<td>No Congestion</td>
</tr>
<tr>
<td>Capacity-constrained</td>
<td></td>
<td>Centralized</td>
<td></td>
</tr>
</tbody>
</table>

- No Congestion
Problem Definition

AV-Traveler Assignment Problem

Sets and Indices

- Let $T$ be the set of known travelers
  - Future travelers will make requests, but these requests are unknown
  - $i \in T$
- Let $U$ be the set of unassigned travelers  
  - Traveler State 1
- Let $A$ be the set of assigned travelers  
  - Traveler State 2
- Let $IV$ be the set of in-vehicle travelers  
  - Traveler State 3
- Let $S$ be the set of served travelers  
  - Traveler State 4
- $i \in U \cup A \cup IV \cup S$
- Let $V$ be the set of AVs in the fleet
  - $j \in V$
  - Let $I$ be the set of idle vehicles  
    - AV State 1
  - Let $P$ be the set of en-route pick-up vehicles  
    - AV State 2
  - Let $D$ be the set of en-route drop-off vehicles  
    - AV State 3
  - $j \in I \cup P \cup D$
Problem Definition

AV-Traveler Assignment Problem

Traveler and AV Information

• traveler $i$:
  • Static Information
    • Pick-up location and drop-off location
    • Request time = earliest pickup time $r_i$
    • Group Size
  • Dynamic Information
    • Current location
    • Elapsed wait time
    • State $\in U \cup A \cup IV \cup S$

• AV $j$:
  • Static Information
    • Capacity
  • Dynamic Information
    • Current location
    • Current destination
    • Current load
    • State $\in I \cup P \cup D$
    • Next traveler to pick-up and/or drop-off
Problem Definition

AV-Traveler Assignment Problem

Parameters

- \( c_{ij} \): travel distance between traveler \( i \) and AV \( j \)
  - Also, the remaining wait time of traveler \( i \) if picked-up by AV \( j \)
- \( t_i \): request time of traveler \( i \in U \cup A \) \( \leftarrow \) earliest pickup time
- \( \tau \): current time
- \( w_i = \tau - t_i \): elapsed wait time of traveler \( i \in U \cup A \)
- \( s_{ij} = 1 \) if traveler \( i \in U \) and AV \( j \in P \) are eligible for a shared-ride
- \( r_j = 1 \) if AV \( j \) is currently eligible to be reassigned
- \( h \): length of hold time before assigning AVs to travelers

Decision Variable

- \( x_{ij} = 1 \) if AV \( j \) assigned to traveler \( i \)
Problem Definition

AV-Traveler Assignment Problem

$w_i$:

$t_i$: request time of traveler $i$ $\leftrightarrow$ earliest pickup time

$\tau$: current time

$w_i = \tau - t_i$: elapsed wait time of traveler $i$
Problem Definition
AV-Traveler Assignment Problem

\[ w_i \]

\[ t_i : \text{request time of traveler } i \leftrightarrow \text{earliest pickup time} \]

\[ \tau : \text{current time} \]

\[ w_i = \tau - t_i : \text{elapsed wait time of traveler } i \]
Problem Definition

AV-Traveler Assignment Problem

- Unassigned
- Assigned
- In-Vehicle
- Served

\[ \tau \]
Problem Definition

AV-Traveler Assignment Problem ↔ Rolling Horizon Optimization

$h$: length of hold time before assigning AVs to travelers

- Unassigned
- Assigned
- In-Vehicle
- Served
Problem Definition

AV-Traveler Assignment Problem ↔ Rolling Horizon Optimization

- Unassigned
- Assigned
- In-Vehicle
- Served

Assign AVs to Travelers
Problem Definition

AV-Traveler Assignment Problem ↔ Rolling Horizon Optimization

- Unassigned
- Assigned
- In-Vehicle
- Served

Assign AVs to Travelers

This research: test different strategies to assign AVs to Travelers
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No mathematical programming required
AV-Traveler Assignment Strategies

Optimization-based Strategies

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Requires mathematical programming
Mathematical Formulation

Static AV-Traveler Assignment Problem

Case 1: \( |T| < |V| \)  \# Travelers < \# AVs

\[
\min \left( \sum_{i \in T} \sum_{j \in V} c_{ij} x_{ij} \right)
\]

s.t.

\[
\sum_{j \in V} x_{ij} = 1 \quad \forall i \in T
\]

\[
\sum_{i \in T} x_{ij} \leq 1 \quad \forall j \in V
\]

\[
x_{ij} \in \{0,1\} \quad \forall i \in T, \forall j \in V
\]
Mathematical Formulation

Static AV-Traveler Assignment Problem

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**# Travelers < # AVs**

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\[x_{ij} \in \{0, 1\} \quad \forall i \in T, \forall j \in V\]

All travelers must be assigned to an AV

An AV can only be assigned to one traveler

Min. cost AV-traveler matching
Mathematical Formulation

Static AV-Traveler Assignment Problem

Case 2: \(|T| > |V|\)  \# Travelers > \# AVs

\[
\begin{align*}
\min & \left( \sum_{i \in T} \sum_{j \in V} c_{ij} x_{ij} - \gamma w_i x_{ij} \right) \\
\text{s.t.} & \\
\sum_{j \in V} x_{ij} & \leq 1 \quad \forall i \in T \\
\sum_{i \in T} x_{ij} & = 1 \quad \forall j \in V \\
x_{ij} & \in \{0, 1\} \quad \forall i \in T, \forall j \in V
\end{align*}
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Case 2: $|T| > |V|$  
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Min.

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\]

Static AV-Traveler Assignment Problem

Give preference to travelers that have large elapsed wait time

A traveler can only be assigned to one vehicle

Each AV must be assigned to a traveler

Min. cost AV-traveler matching
Assignment Strategies

What differentiates strategies 3-5?

\[
\min \left( \sum_{i \in T} \sum_{j \in V} c_{ij} x_{ij} - \gamma w_i x_{ij} \right)
\]

What travelers \(i \in T\) are included in the assignment strategy?
- \(i \in U\) \(\leftarrow\) Always
- \(i \in A\) \(\leftarrow\) Sometimes
- \(i \in IV \cup S\) \(\leftarrow\) Never

What AVs are included in the assignment strategy?
- \(j \in I\) \(\leftarrow\) Always
- \(j \in P\) \(\leftarrow\) Sometimes
- \(j \in D\) \(\leftarrow\) Sometimes

- Unassigned travelers \(i \in U\) and idle AVs \(j \in I\) are always included in assignment
- **Strategy 4** includes *en-route pick-up AVs* \(j \in P\) in assignment
  - Essentially allows en-route pick-up AVs to be reassigned (i.e. diverted) to new/other traveler requests
  - This then requires **assigned (but not picked-up) travelers** \(i \in A\) to be included in assignment
- **Strategy 5** includes *en-route drop-off AVs* \(j \in D\) in assignment
  - \(c_{ij}\) \(\leftarrow\) need to account for distance to drop-off current passenger and distance to pick-up new traveler