McCormick

Northwestern Engineering

Northwestern University Transportation Center

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

Michael Hyland and Hani Mahmassani

June 9th, 2017

Transport Chicago

http://www.navtejkohli.info/11-accidents-google-self-driven-car/

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

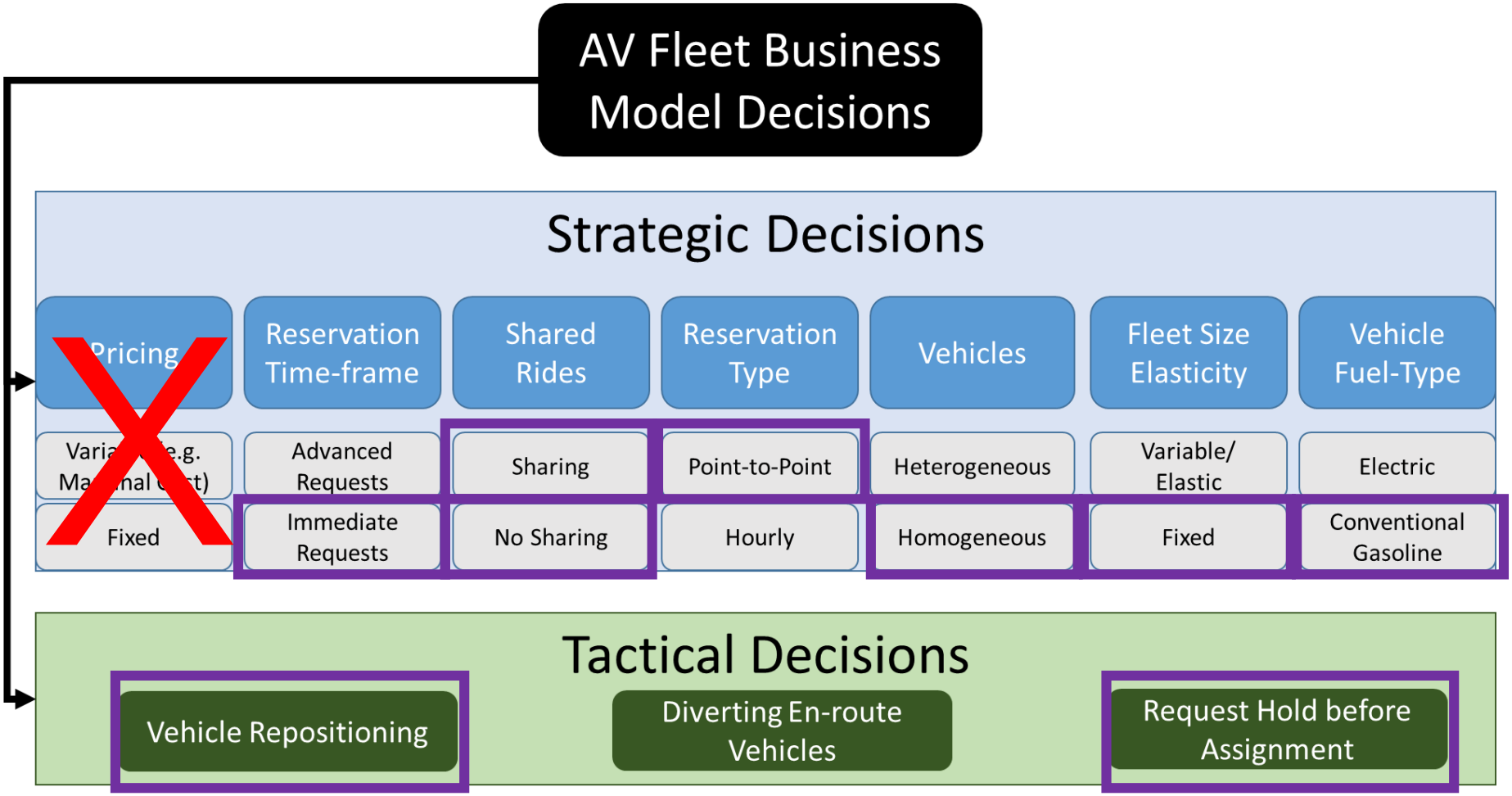
Conceptual Model of AV Fleet Business

- 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.shaneanderson.biz/wp-content/uploads/2015/11/driverlesscarinside.png
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

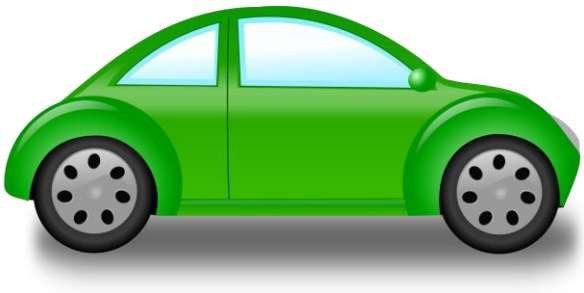


Broad Research Aims

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 ← 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

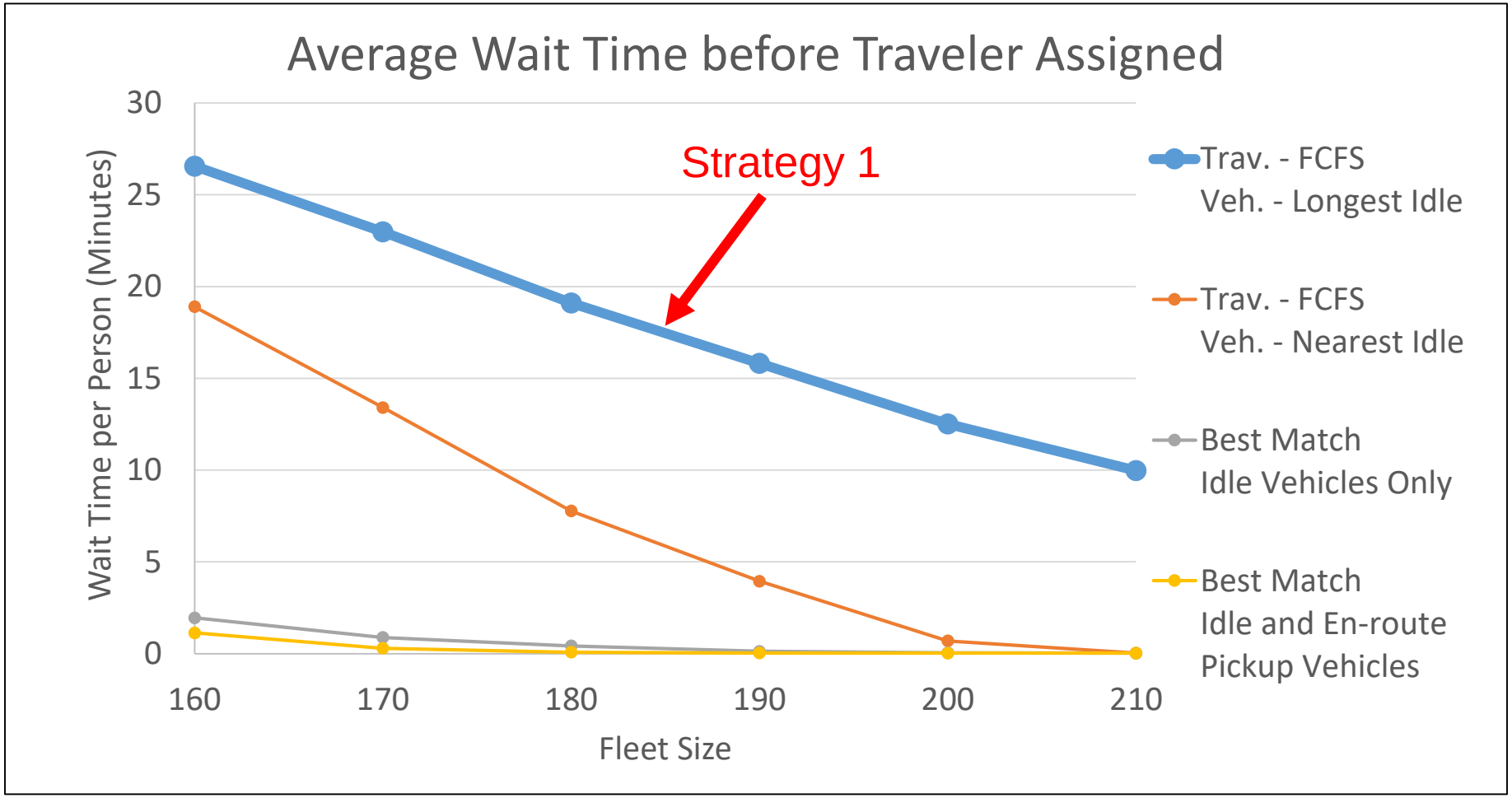
Takeaway 1

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



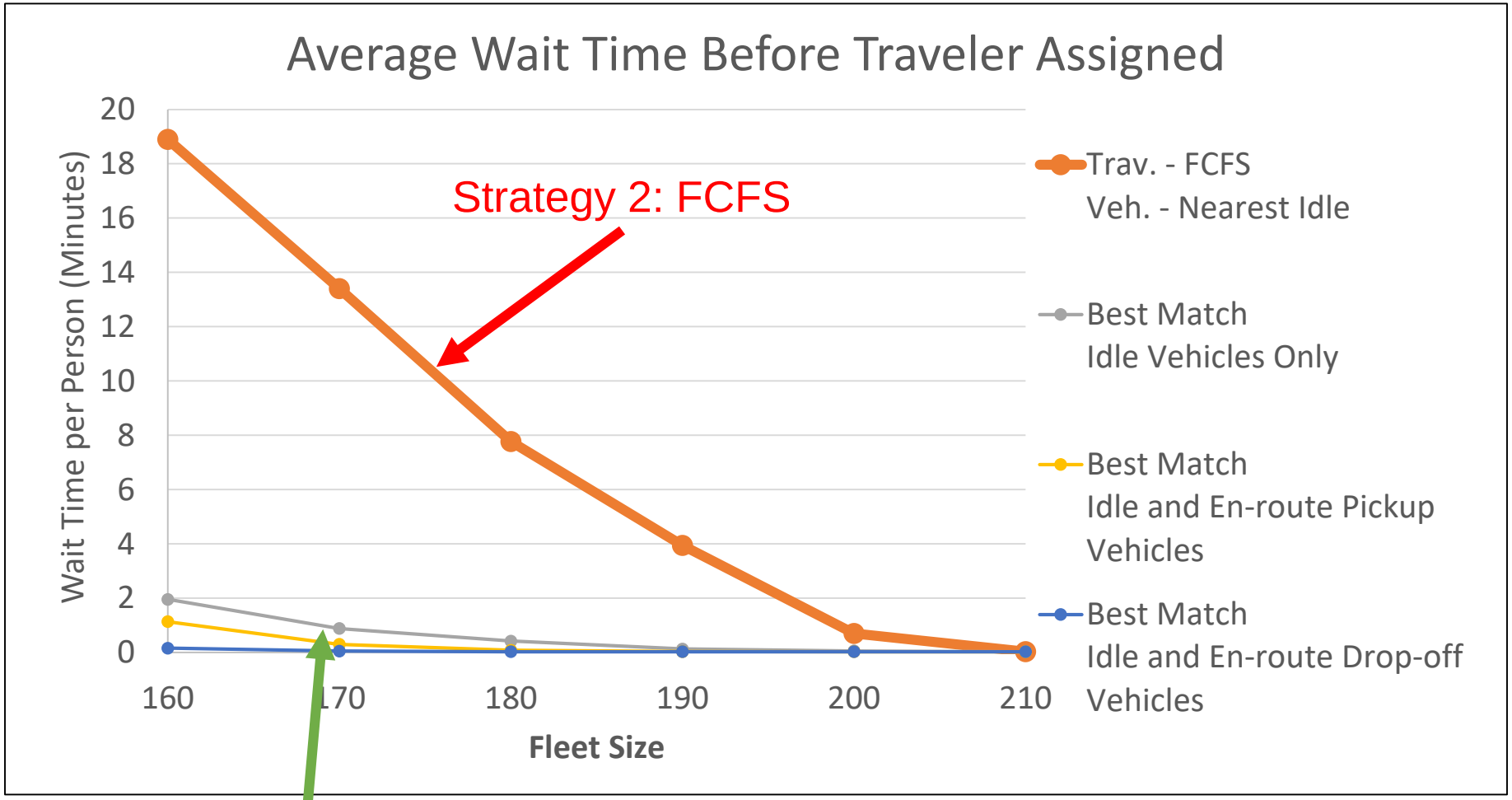
Takeaway 2

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

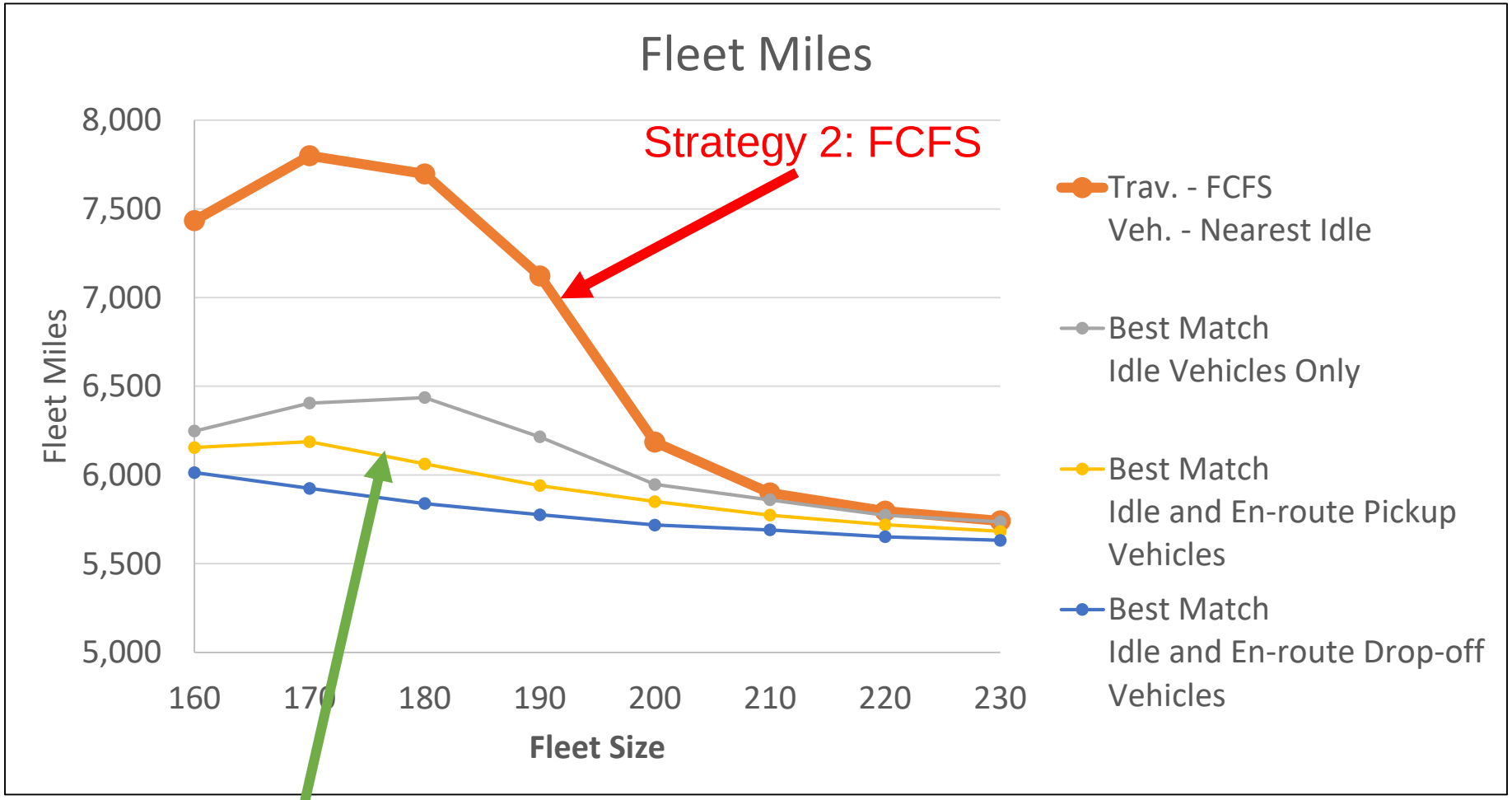
Optimization-based Strategies outperform FCFS



Optimization-base Assignment Strategies

Takeaway 2

Optimization-based Strategies outperform FCFS



Optimization-base Assignment Strategies

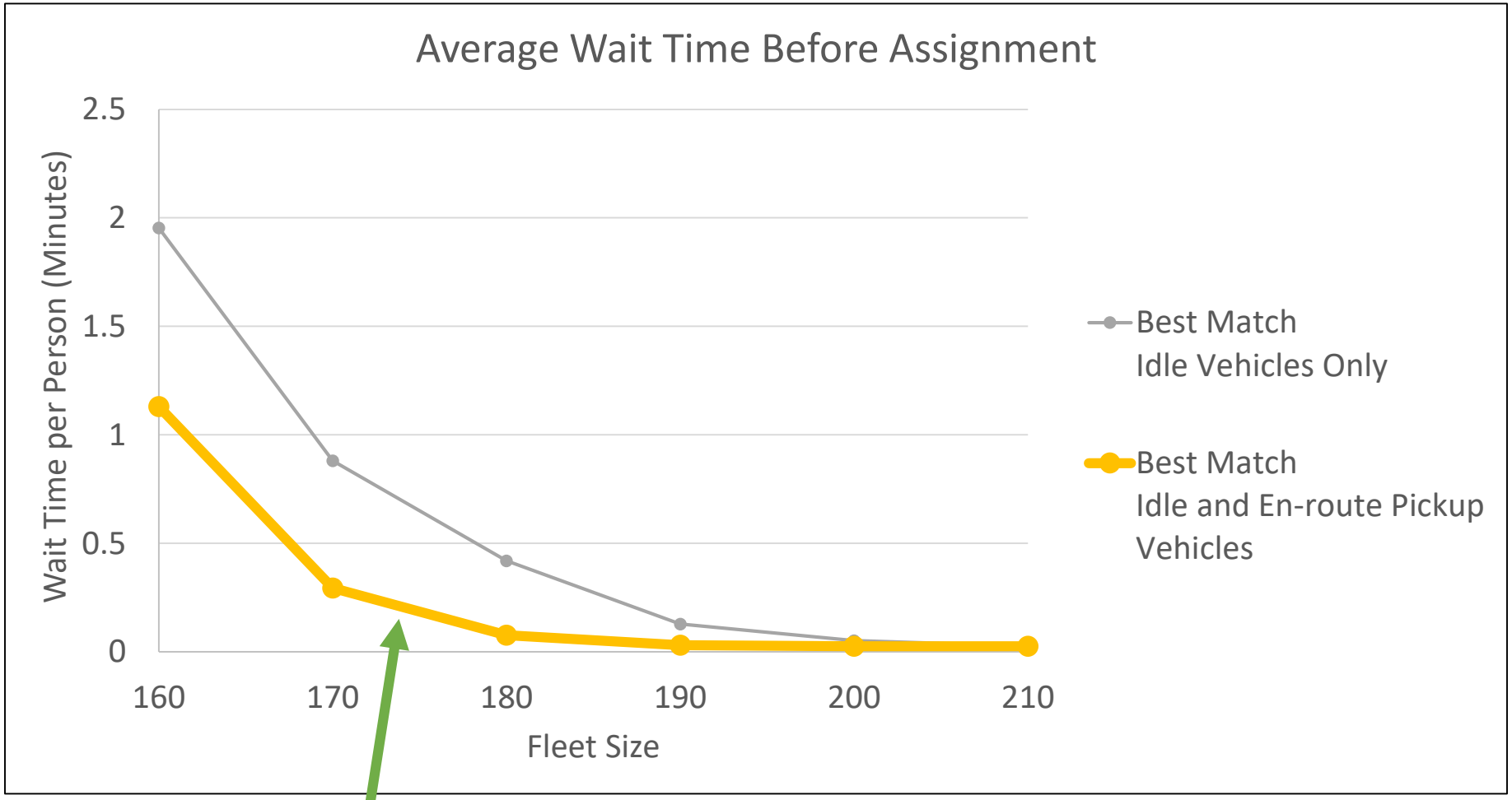
Takeaway 3

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



Strategy 4: Diversions

Takeaway 3

Beneficial to include En-route Pick-up AV Diversions

Strategy 4: Diversions

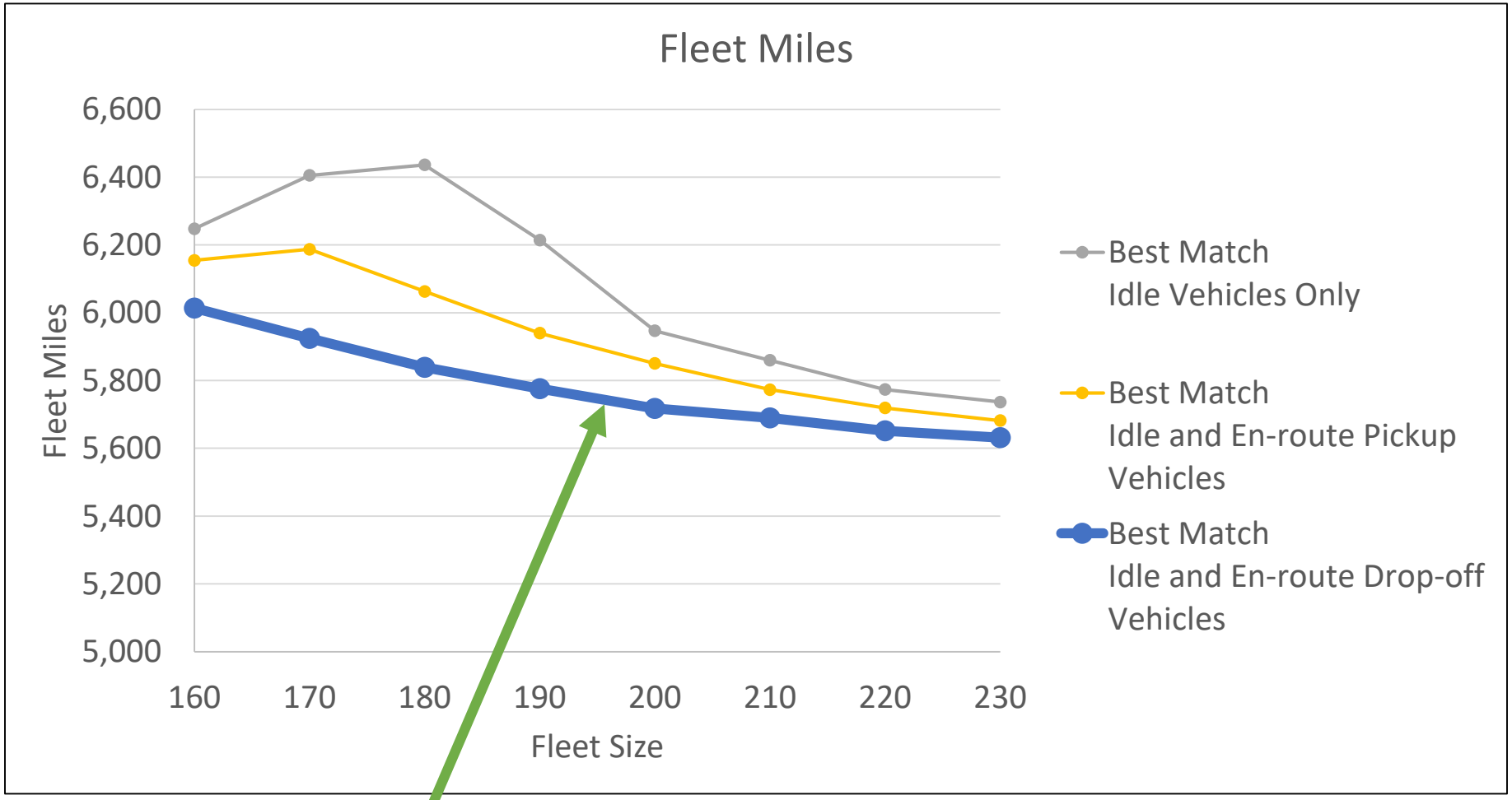
Takeaway 4

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

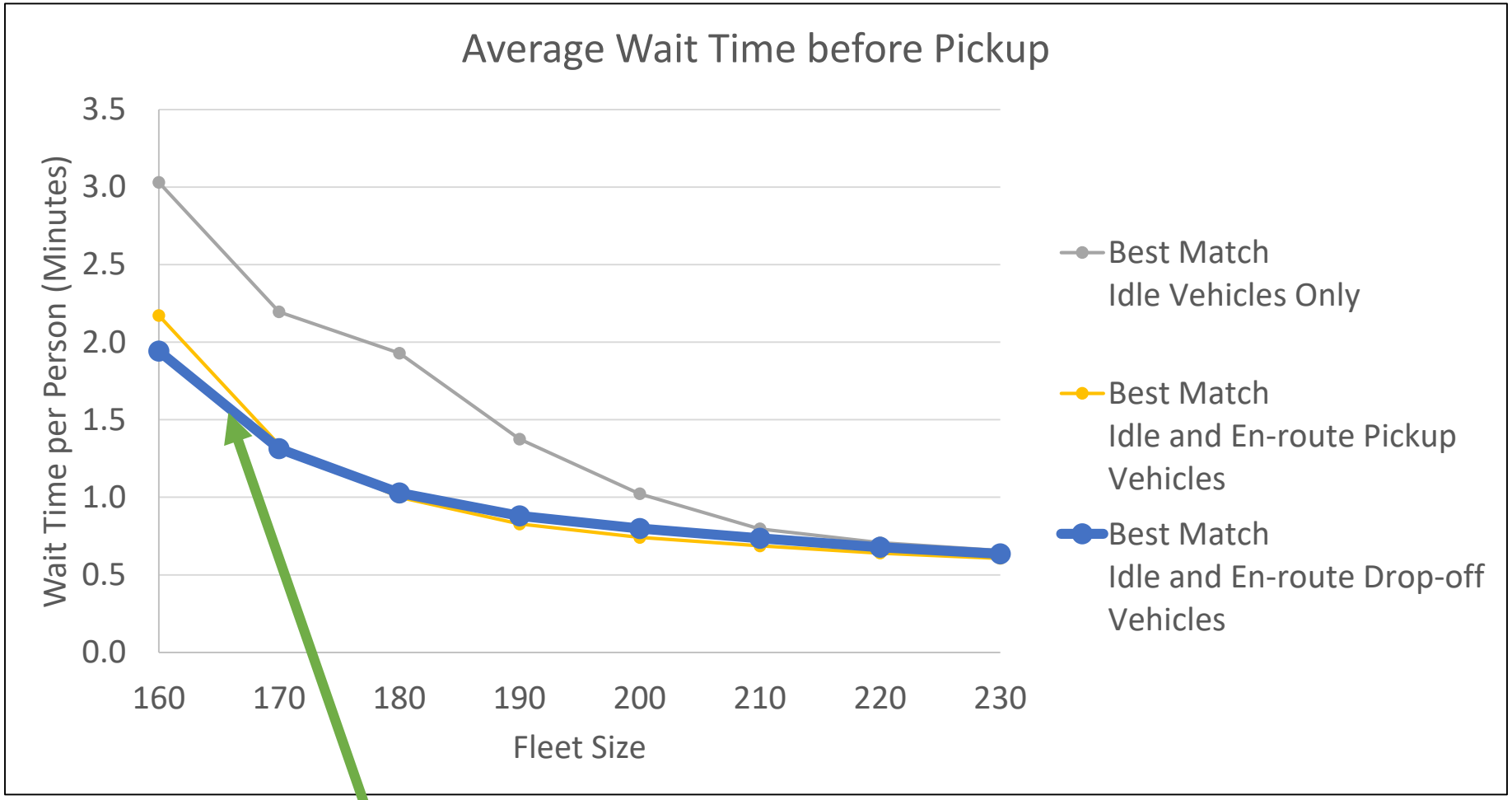
Beneficial to include En-route Drop-off AVs in Assignment



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

Takeaway 4

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

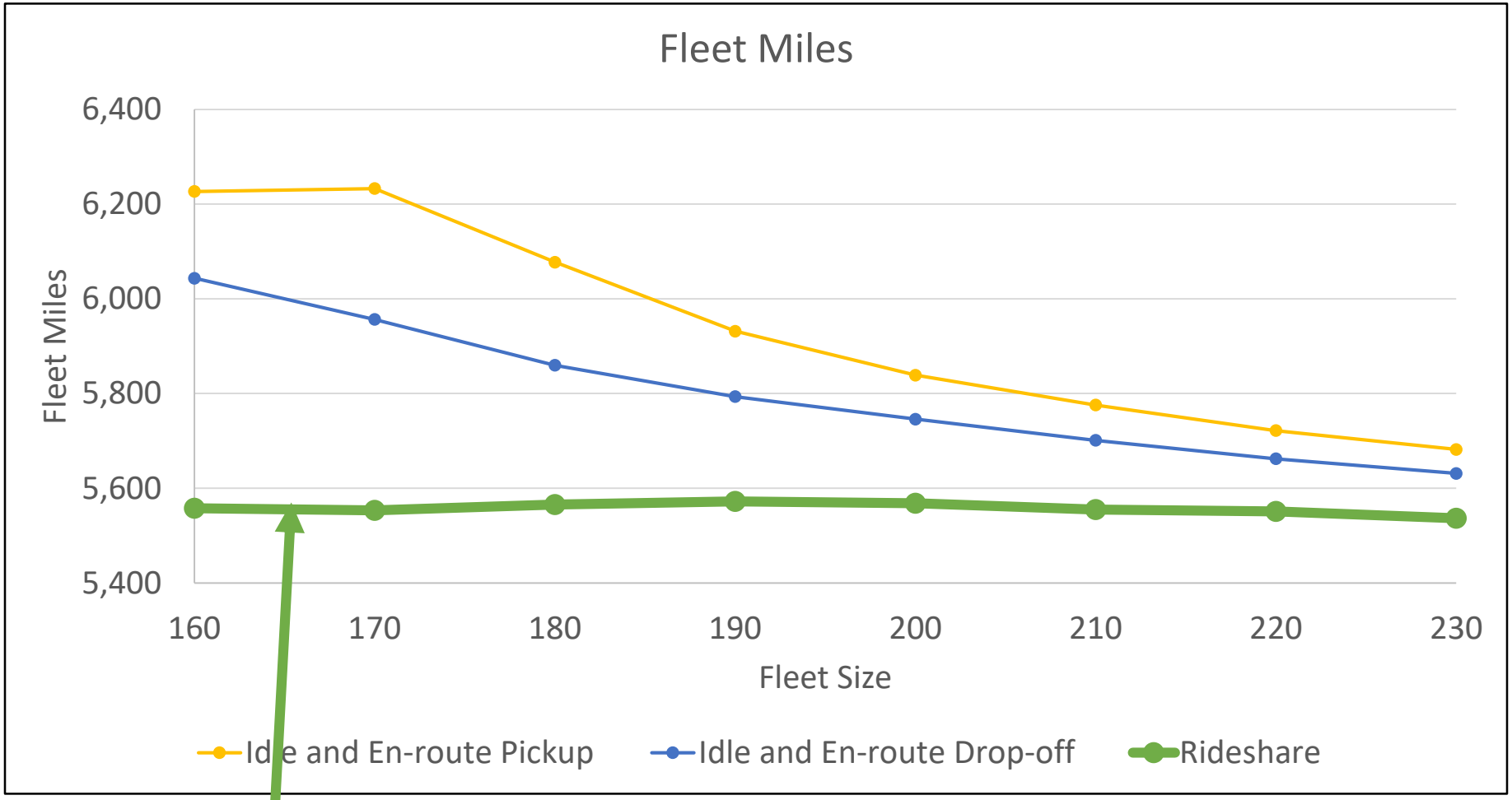


Strategy 5: Include En-route Drop-off AVs in Assignment

Shared-Rides

Takeaway 5

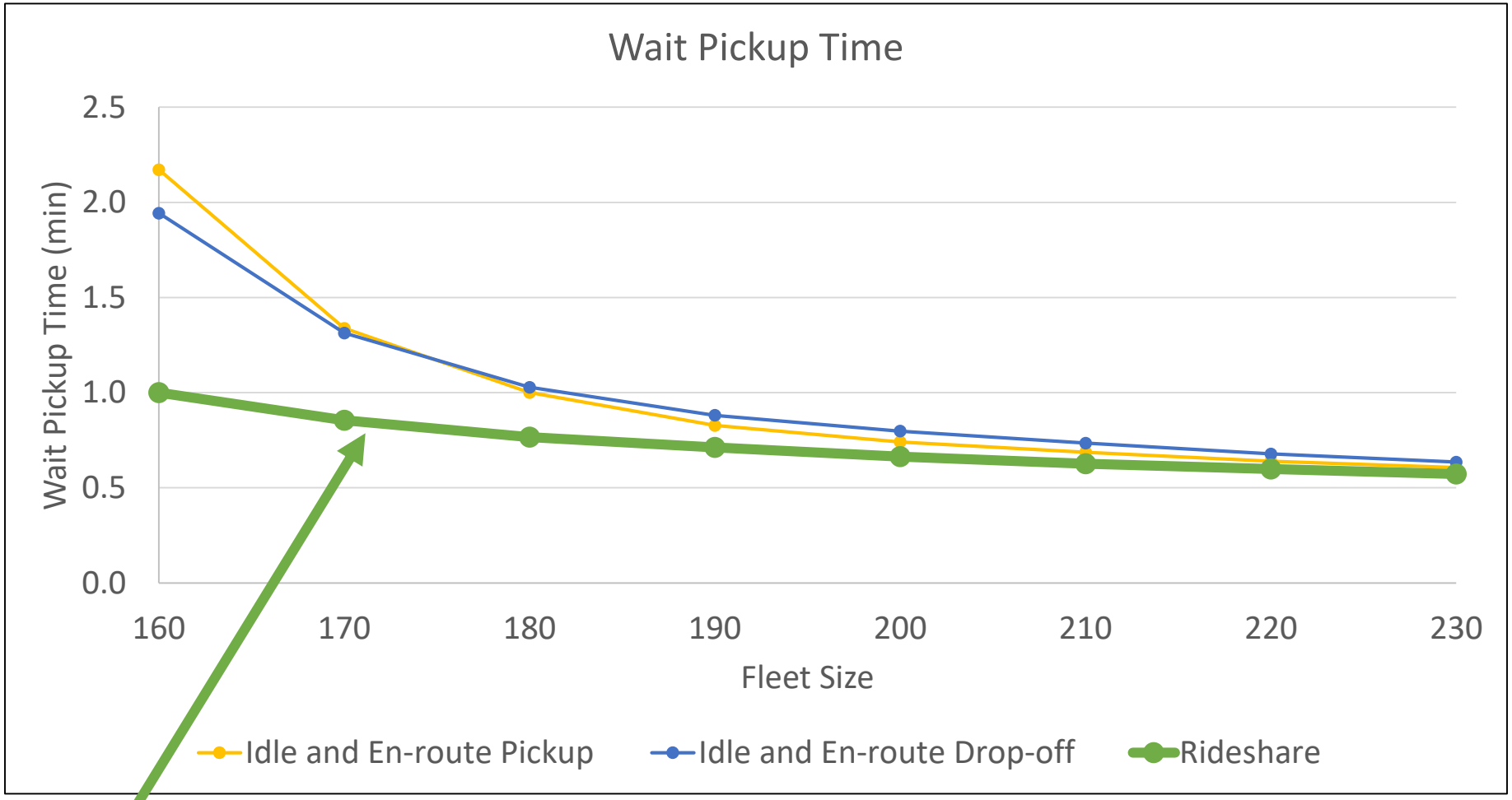
Shared-Rides **reduce Fleet Miles** and Traveler Wait Time with small increase in Traveler IVTT



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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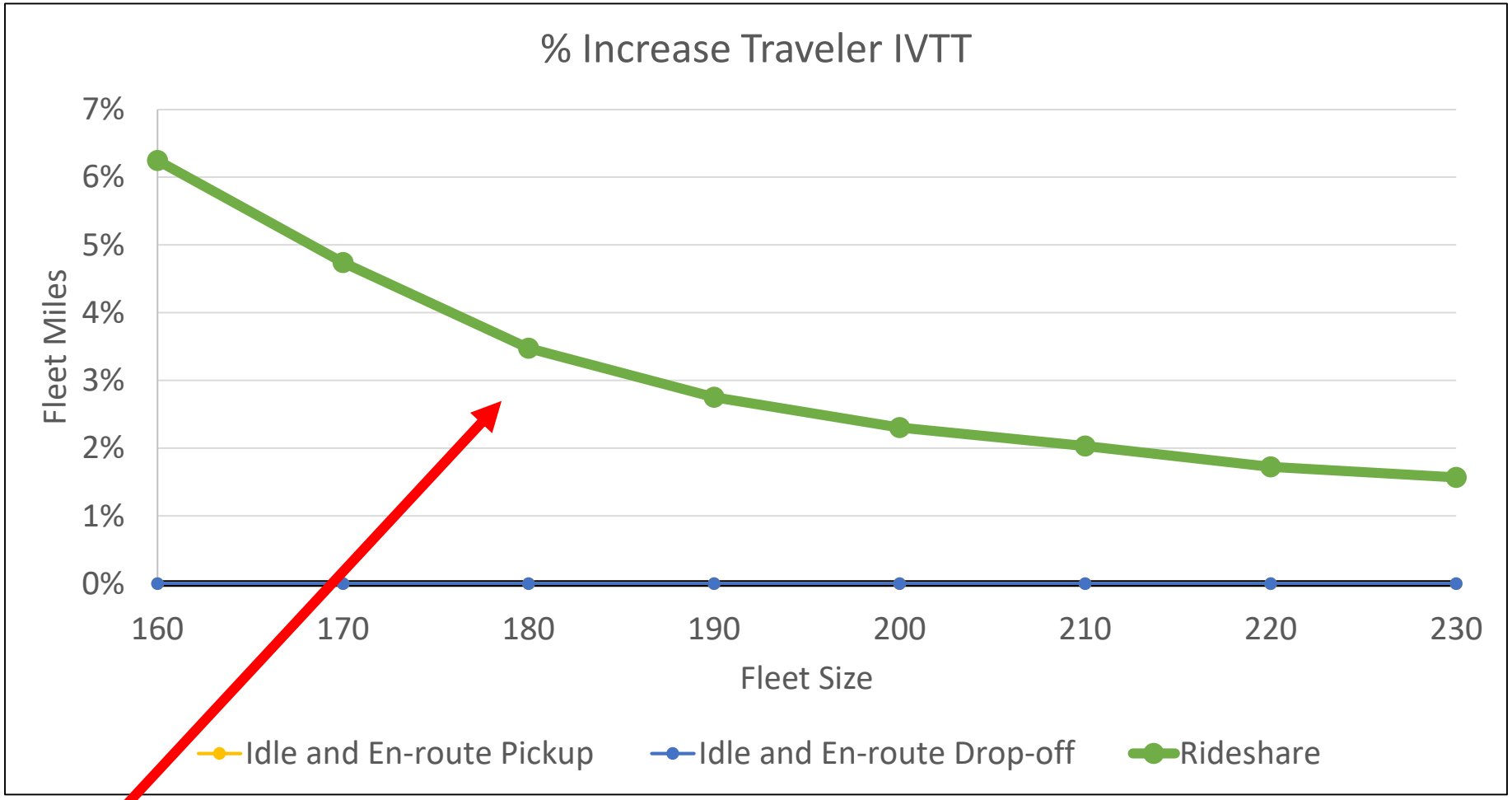
Takeaway 5

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!

Michael Hyland

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Extra Slides

Mathematical Formulation of AV-Traveler Assignment Problem

Problem Definition

Conceptualization

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

AVs

- Multi-vehicle
  - Fixed Fleet Size
- Homogenous
- Capacity-constrained

Travelers

- Pickup and Drop-off
- Immediate Requests
- Must be served

Information

- Dynamic
- Stochastic
- Global
- Centralized

Network

- Manhattan
- Deterministic Travel Times
- 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 State2
  - 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

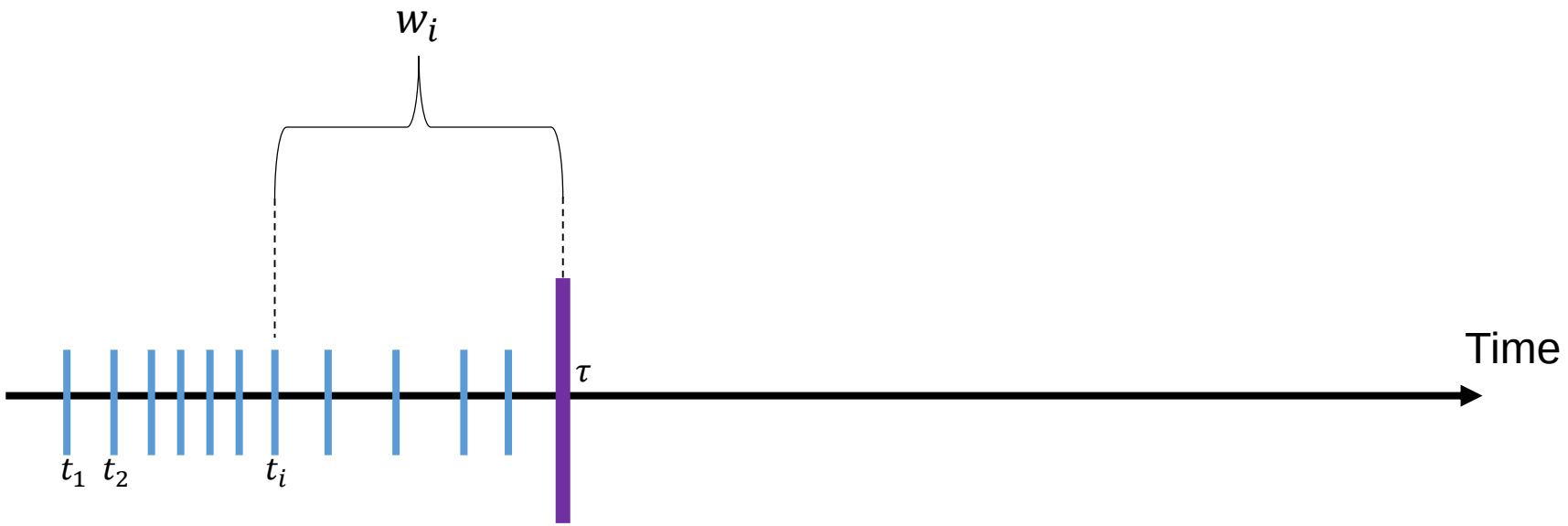
- c_{ij}: travel distance between traveler i and AV j
  - Also, the remaining wait time of traveler i if picked-up by AV j
- t_i: request time of traveler $i \in U \cup A$ ← earliest pickup time
- τ: current time
- $w_i = \tau - t_i$: elapsed wait time of traveler $i \in U \cup A$
- $s_{ij} = 1$ if traveler $i \in U$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



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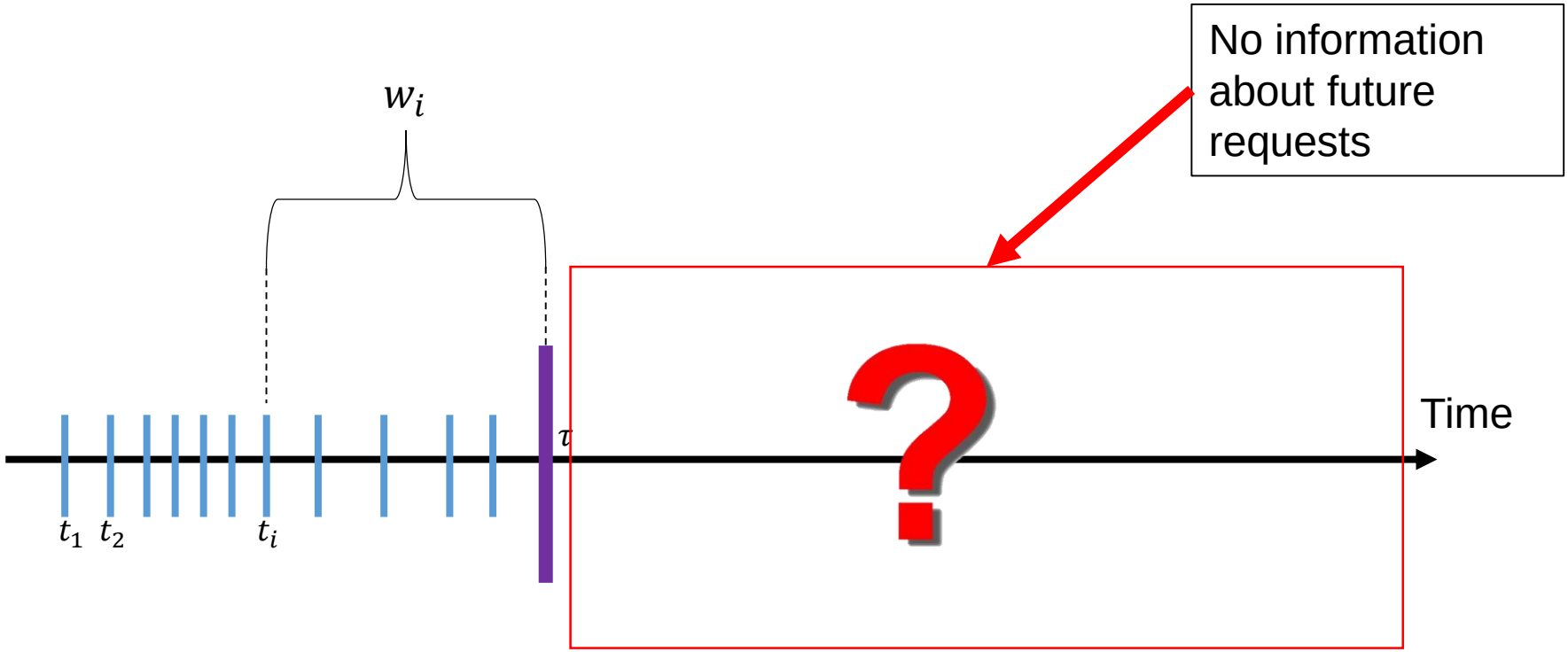

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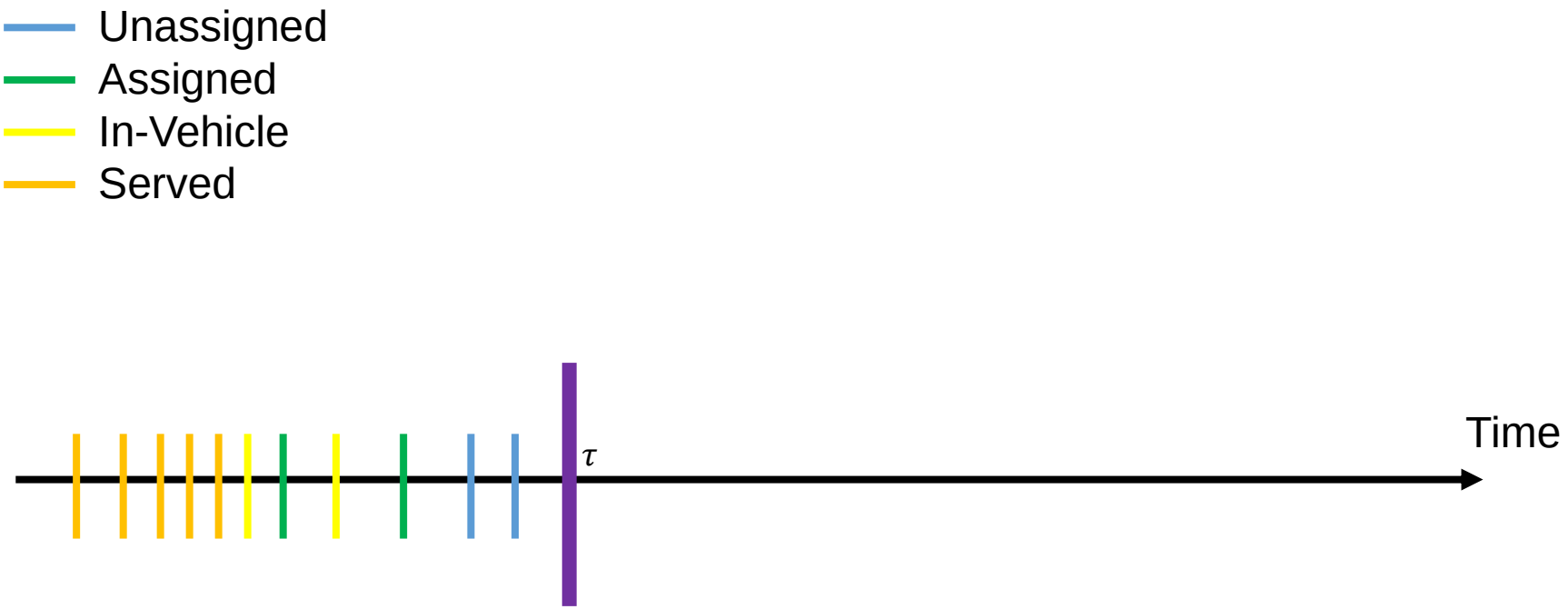
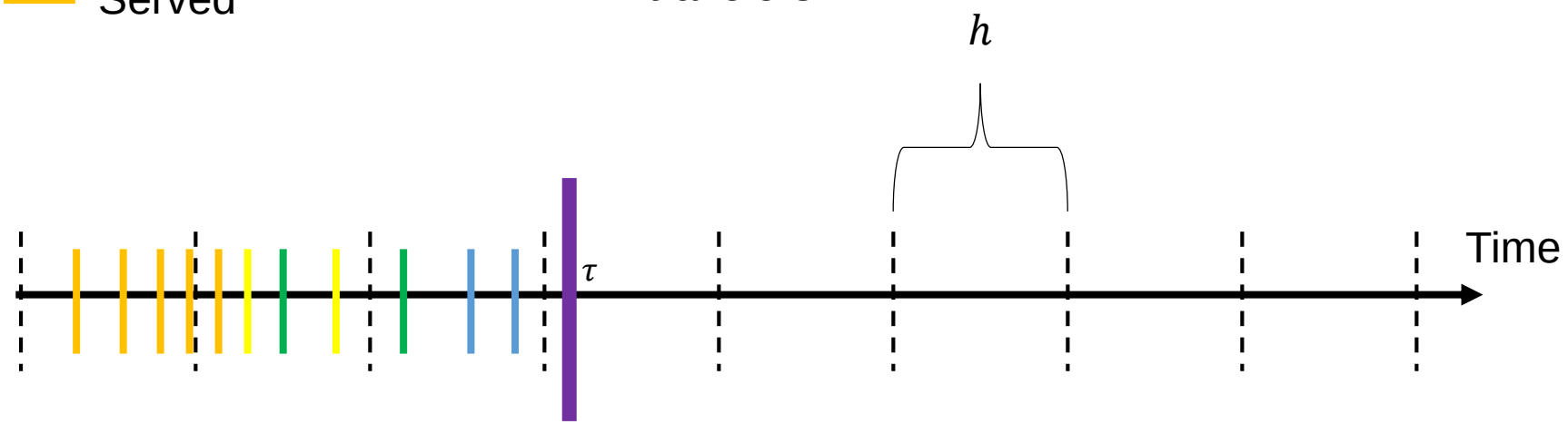


Problem Definition

AV-Traveler Assignment Problem ← Rolling Horizon Optimization

- Unassigned
- Assigned
- In-Vehicle
- Served

h: length of hold time before assigning AVs to travelers



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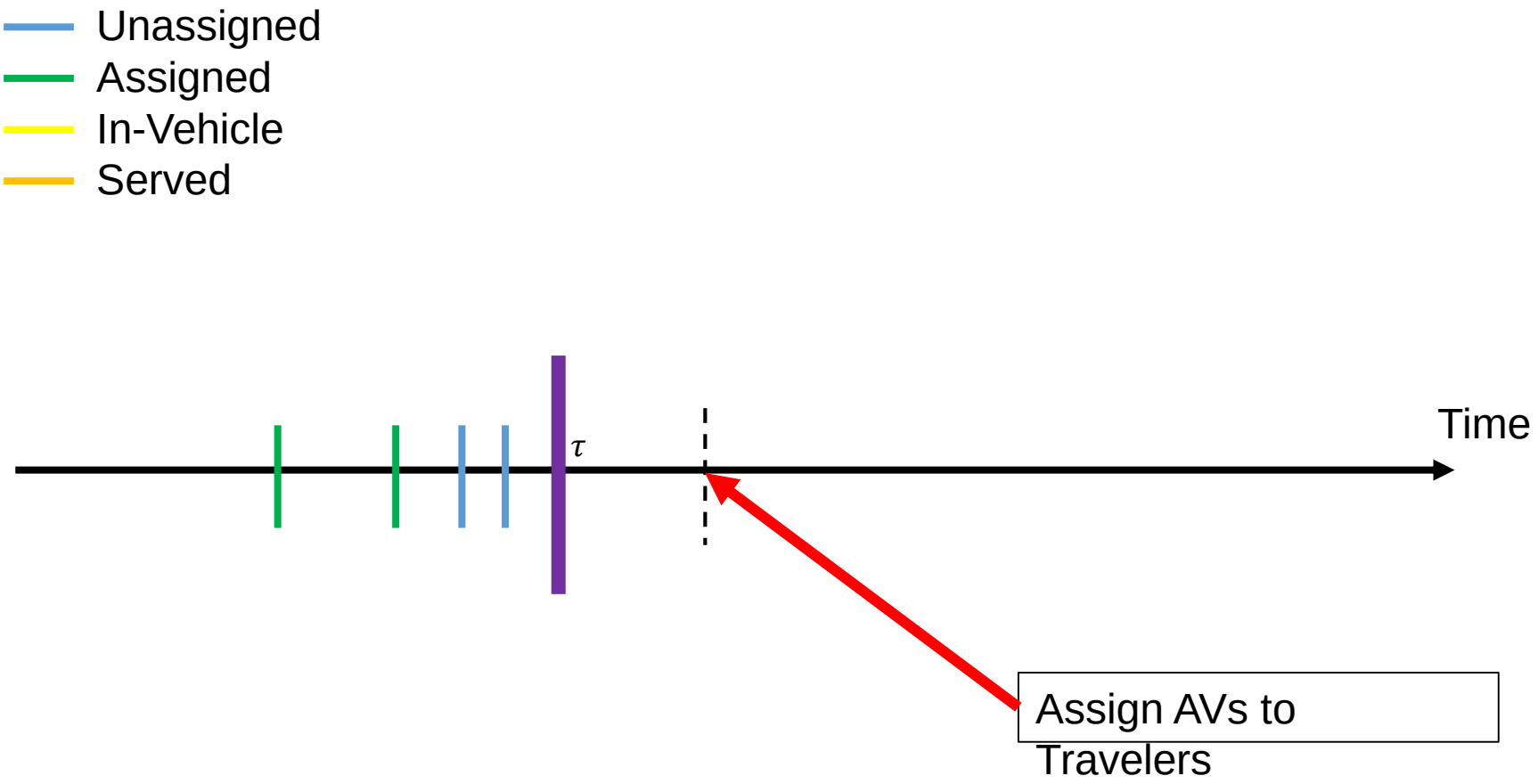

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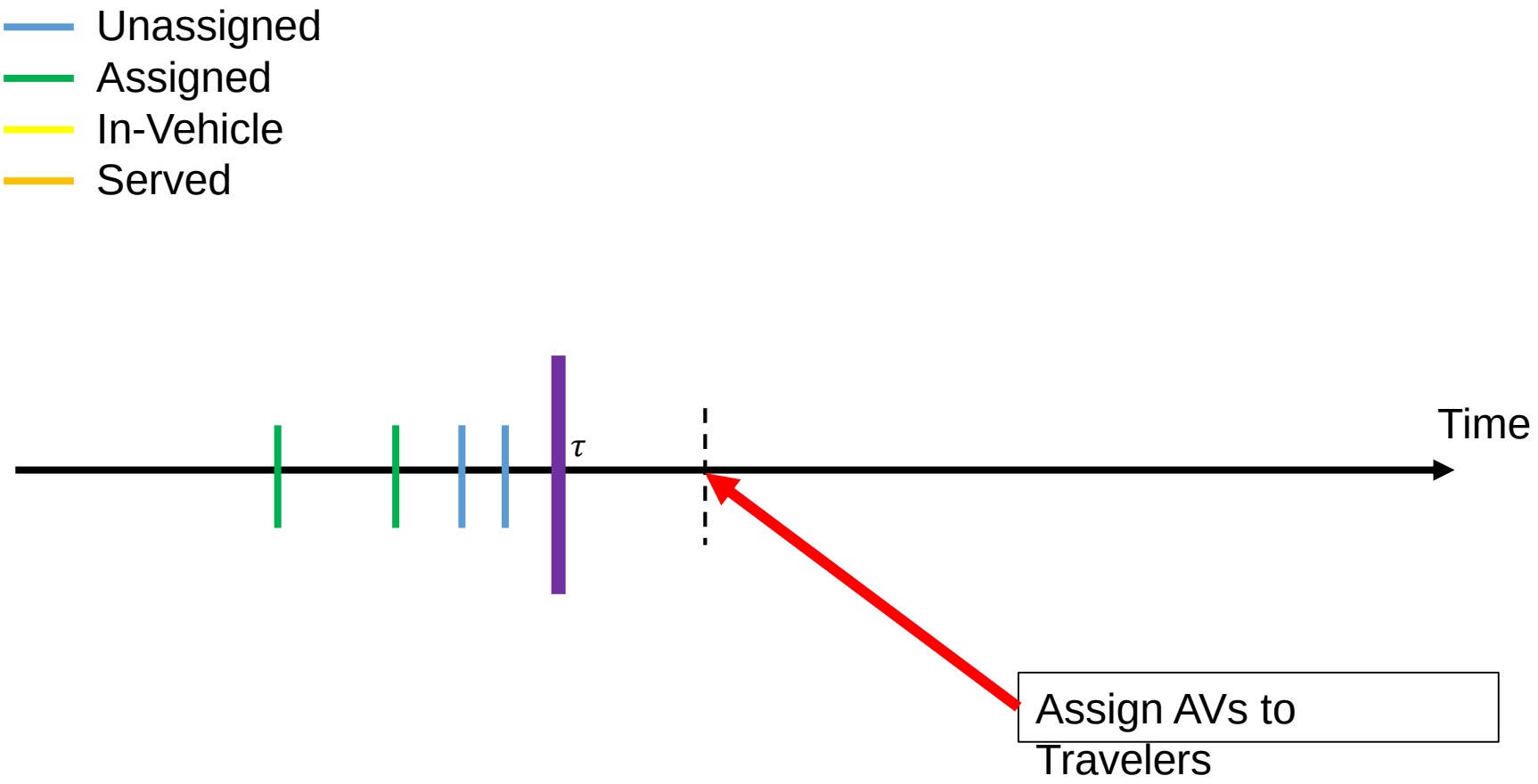

This research: test different strategies to assign AVs to Travelers

AV-Traveler Assignment Strategies

Simplistic Strategies

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No mathematical programming required

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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.

$$\sum_{j\in V} x_{ij} = 1 \qquad \forall i \in T$$

$$\sum_{i\in T} x_{ij} \leq 1 \qquad \forall j \in V$$

$$x_{ij} \in \{0,1\} \qquad \forall i \in T, \forall j \in V$$

Mathematical Formulation

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Min. cost AV-traveler matching

All travelers must be assigned to an AV

An AV can only be assigned to one traveler

Mathematical Formulation

Static AV-Traveler Assignment Problem

Case 2: $|T| > |V|$ **# Travelers > # AVs**

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

s.t.

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Mathematical Formulation

Static AV-Traveler Assignment Problem

Case 2: $|T| > |V|$ **# Travelers > # AVs**

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

Give preference to travelers that have large elapsed wait time

s.t.

A traveler can only be assigned to one vehicle

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

Min. cost AV-traveler matching

Each AV must be assigned to a traveler

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

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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?

- $i \in U$ ← Always
- $i \in A$ ← Sometimes
- $i \in IV \cup S$ ← Never

What AVs are included in the assignment strategy

- $j \in I$ ← Always
- $j \in P$ ← Sometimes
- $j \in D$ ← 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} ← need to account for distance to drop-off current passenger and distance to pick-up new traveler