

Experimental Comparison of Autonomous Vehicles Scheduling Algorithms

With Battery Management in a Fixed Line Service

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Master Thesis, Computer Science

1. The Problem: Autonomous Vehicles in a Fixed Line Transportation Service
2. Model Outline
3. Numerical Experiments

The Problem: Autonomous Vehicles in a Fixed Line Transportation Service

The Problem

Scheduling autonomous vehicles' activities in a circular line transportation service with dynamic bookings

Goals

- Run simulations as close as possible to **real world** conditions
- Get insights about strategical choices to improve the:
 - **passengers level of service**
 - **vehicles operating costs**

How

- Propose a **dynamic fleet size** scheduling strategy making use of **demand forecasting**
- Test how the system's performance metrics react to different **scenarios** and **scheduling strategies**

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Model Outline

Loop

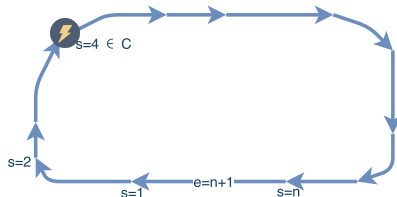


Figure 1: Example of a circular route

- Set of stations $S = 1, \dots, n$
- Set of charging stations $C \in S$
- Stop s is mandatory or optional
- Speed of edge e at time t : $speed_t^e$

Vehicles

- Vehicles fleet: V
- Vehicle $v \in V$:
 - Capacity: c^v
 - Maximum battery: q^v Recharging rate: α^v Consumption rate: β^v
 - Maximum speed: s^v

Dynamic Information at time t

- Battery level: I_t^v
- Number of passengers in vehicle: o_t^v
- Distance to the next vehicle on the loop: $next_t^v$
- Stopping duration: $wait_t^v$
- Indicator if vehicle is charging: x_t^v

AUTONOMOUS VEHICLES TRANSPORTATION MODEL

Vehicles

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Bookings

- Booking from stop i to j : $b_{i,j}$, made at time t^b for n^b passengers
- If it has been satisfied $D_b = 1$:
 - Pickup time: p^d
 - Drop-off time: d^d
 - Satisfied by vehicle v^d
 - Waiting time: $w^b = p^b - t^b$
 - Journey time: $\rho^b = d^b - p^b$
- Set of bookings which have been satisfied: $B^* \in B$

Demand

dem_{t^*} : the number of bookings which have been made between t^* and $t^* + 1h$, so the number of bookings with $t^* \leq t^{*b} < (t^* + 1h)$

t^* is a discrete hourly timestamp

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VEHICLES OUTPUT METRICS

Metrics at the end of the scheduling horizon of one day (midnight to midnight)

Battery

- *battery^v*: sum of the battery changes over the scheduling horizon when the vehicle is not charging
- *batteryCost* = $\sum_{v \in V} \text{battery}^v$

Occupancy

- *avgOccupancy^v*: average occupancy of vehicle v
 - *loadFactor^v*: doesn't consider time a vehicle is going to charge.
- Passenger-battery over seat-battery:

$$\frac{\sum_{b \in B^*} \text{battery}^b * n^b}{\text{battery}^v * c^v}$$

CUSTOMERS' LEVEL OF SERVICE OUTPUT METRICS

Waiting Time

- *avgWaitingTime* = $\frac{\sum_{b \in B^*} w^b}{|B^*|}$
- *stabilityWaitingTime* = $\max_{b^+ \in B^*} w^{b^+} - \min_{b^- \in B^*} w^{b^-}$

Journey Time



- *avgJourneyTime* = $\frac{\sum_{b \in B^*} \rho^b}{|B^*|}$

Completed Bookings Percentage

- *completedBookings* = $\frac{|B^*|}{|B|}$

Numerical Experiments

Testing Environment

- Scheduling Horizon $H = 1$ hour
- Demands $dem_0 = 27$
- Fleet size $|V| = 5$
- Heterogeneous fleet $\forall v \in V$.
 - $c^v = 10$
 - battery $q^v = 1$, charging/consumption rates = 1
 - Maximum speed $s^v = 20\text{km/h}$
- Delphi Graph: $S = 1, \dots, 32$
- Each simulation run 3 times, average reported
- **Reporting** application fetches vehicles' logs every second



Vehicles

- Simulated concurrently following an actor model, each vehicle being an actor
- Actor step: position + battery updated every $1000/\textit{rate}$ [ms]
- Trade-off between:
 - complexity of computation: if *rate* is **too high** => actor system has too many unhandled messages
 - precision: if *rate* is **too low** => vehicles skip stops
- *rate* = 3

SIMULATION SETTINGS

Time Synchronization

- Synchronize simulated time which is accelerated r times in the different applications, using the system clock
- $simTime = startTimestamp + (currentSystemTime - startTimestamp) * r + shiftDuration$

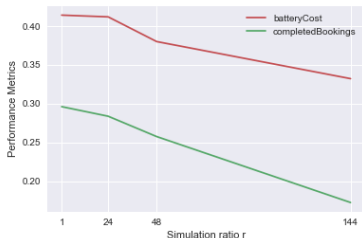


Figure 2: Performance metrics at growing simulation ratio

Table 1: Difference to $r = 1$

	$r = 24$	$r = 144$
<i>batteryCost</i>	0.5%	21%
<i>completedBookings</i>	4%	52%

=> $r = 24$ is a reasonable choice!

Time Consistency Between Applications

Difference between $simTime^b$ at which `World Simulator` sends booking b and the reported time in the logs from `Reporting` is not more than 55 seconds and on average 5 seconds

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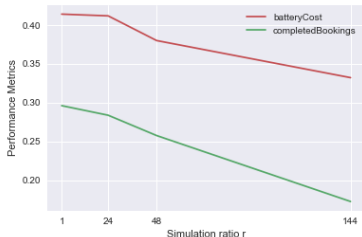


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Time Consistency Between Applications

Difference between $simTime^b$ at which **World Simulator** sends booking b and the reported time in the logs from **Reporting** is not more than 55 seconds and on average 5 seconds

Goal

Maintain equal distance between vehicles to avoid bus bunching effect

Strategy

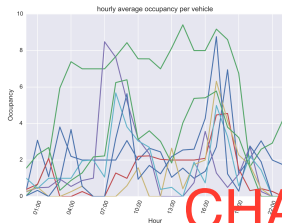
- *default*: default waiting time in seconds at a station
- When a vehicle v arrives at a station it waits $wait_{simTime}^v = \text{default} * \text{ratio}$, with *ratio* computed as follows:
 - Ideal distance: $\text{ideal} = \text{len} / |V^*|$, V^* being the set of active vehicles on the line
 - $\text{ratio} = \text{next}_{simTime}^v / \text{ideal}$
 - Bounded by *waitMin* and *waitMax*

Testing Scenario

- Delphi Site: $S = 1, \dots, 32$
- Scheduling horizon: $H = 1$ day (midnight to midnight)
- Week-day bookings from Samira (generated analyzing traffic info from HERE map)
- Heterogeneous fleet size $|V| = 8$
- Speed of edges at any time $\text{speed}_t^e = 20\text{km/h}$
- Charging stations: 10 at the same place on the loop

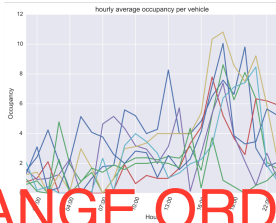
Constant $wait_t^V$

default = 20 [s], ratio = 1



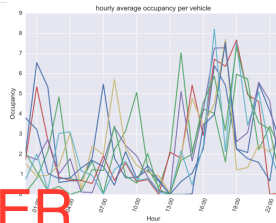
Optional Stops

default = 20 [s], average: 24 [s]



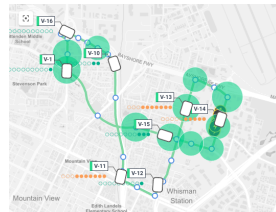
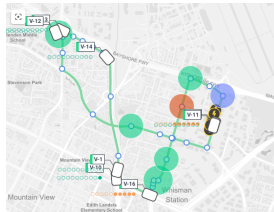
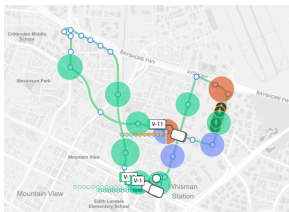
Adapting $wait_t^V$

default = 20 [s], average: 35 [s]

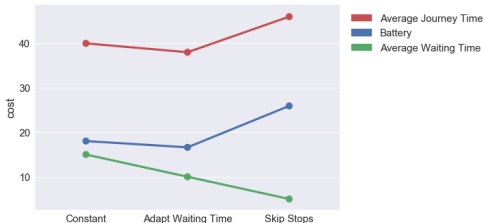


CHANGE ORDER

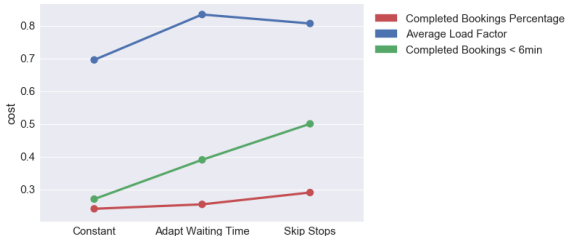
simTime = 6:00 am



PERFORMANCE METRICS COMPARISON FOR HEADWAY



AVG LOAD FACTOR



Incentives

- Demand **varies** through the scheduling horizon
- System gathers real-life data and build prediction models through a machine learning pipeline
=> reasonable to assume that demand can be predicted
- Demand high and not enough vehicles => passengers can't board in and **increase waiting time**
- Demand low and too many vehicles => vehicles **running empty** (not efficient)
- Need to find the right moment to send vehicles to charge

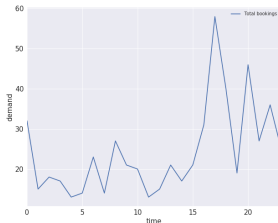


Strategy

- Decide how many vehicles need to be active at each hour of the scheduling horizon based on the demand.
- Need to decide:
 - How the fleet is **rescheduled** when the number of vehicles needed on the line changes
=> send the vehicles with the lowest battery level to charge, reactivate the ones with the highest battery level
 - What is the **demand**
=> number of bookings made within an hour
 - What is the **balance** between quality of service VS cost of the running vehicles
=> define cost function

DEMAND AND SIMULATIONS

Demand distribution through the day



Demand Frequency



Generating Data

- Simulations with scheduling horizon $H = 1h$ => no battery management's noise
- $\forall dem \in D = \{13, 15, 21, 23, 25, 27, 31, 36, 40, 46, 58\}$ simulate with fleet size $|V| \in [2, 10]$
- Gather all **performance metrics**
- Time between two consecutive bookings: $1h/dem$
- **Clean** the data: replace values lower than 5th quantiles and higher than 95th quantiles

DYNAMIC FLEET SIZE

Data: Scheduling horizon H , maximum fleet size V^{max} , optimal fleet size function $optFleet(dem)$

Result: Optimal fleet size at each hour t^* of the scheduling horizon H

$precFleetSize = 0$;

for each hour $t^* \in T^*$ **do**

$optFleet_{t^*} = \min(optFleet(dem_{t^*}), V^{max})$;

$\Delta_{t^*} = optFleet_{t^*} - precFleetSize$;

if $\Delta_{t^*} > 0$ **then**

 | create increase fleet size event by Δ_{t^*}

end

else

 | create decrease fleet size event by $-\Delta_{t^*}$

end

$precFleetSize = optFleet_{t^*}$;

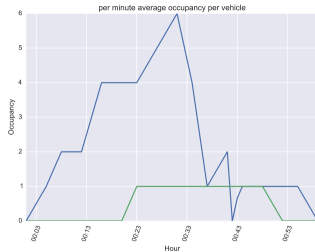
end

Algorithm 1: Dynamic Fleet Size Algorithm

EXTREME SIMULATION EXAMPLES

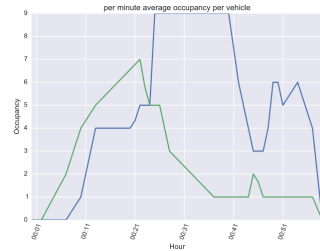
$dem = 13$

$|V| = 2, WT = 14, CBP = 0.61$



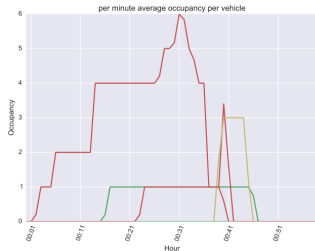
$dem = 58$

$|V| = 2, WT = 12, CBP = 0.31$

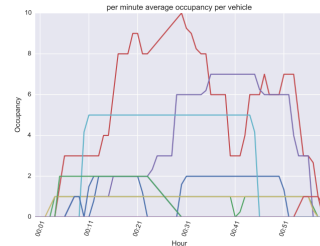


Texte
Texte

$|V| = 10, WT = 6, CBP = 0.69$

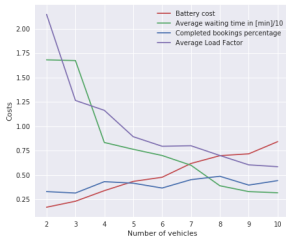


$|V| = 10, WT = 5, CBP = 0.51$



FLEET SIZE' IMPACT ON PERFORMANCE METRICS

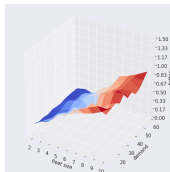
Averages over all demands $\in D$



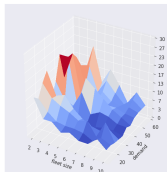
	$ V =2$	$ V $	Difference (in times)
<i>batteryCost</i>	0.17	0.84	4.95
<i>avgWaitingTime</i>	16.8	3.18	-13.62
<i>avgJourneyTime</i>	27	20	-6.54
<i>completedBookings</i>	0.33	0.44	1.34
<i>avgLoadFactor</i>	0.21	0.06	-3.67

Correlation Coeff	Dem	$ V $
<i>batteryCost</i>	-0.09	0.9
<i>avgWaitingTime</i>	0.24	-0.48
<i>completedBookings</i>	-0.39	0.25
<i>avgLoadFactor</i>	0.5	-0.5

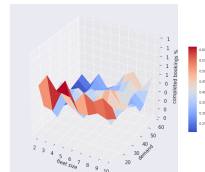
batteryCost



avgWaitingTime



completedBookings



OPTIMAL NUMBER OF VEHICLES: TWO STRATEGIES

completedbookingsratio

1st strategy: Cost Function

$$cost_{dem,|V|} = \frac{batteryCost + avgWaitingTime}{e^{completedBookings}}$$

batteryCost and *avgWaitingTime* normalized by feature scaling $(x - min)/(max - min)$ for each group of same *dem*

- optimal fleet size for *dem*: $|V|$ which minimizes the cost function:

$$\min_{V \in [2,10]} (cost_{dem,|V|})$$

=> For *dem* = 13 we obtain *optFleet* = 3, which grows linearly to *dem* = 58 with *optFleet* = 8 ($R^2 = 0.85$)

2nd strategy: Level of Service Constraint

- Find function describing waiting time: $avgWait_{dem,|V|}$
- Optimal fleet size: minimum $|V|$ such that $avgWait_{dem,|V|}$ is under an acceptable threshold (6 minutes)

Function $avgWait_{dem,|V|}$

- Add dummy variables for each group of same dem to overcome multicollinearity
- **Linear regression**: $avgWaitingTime \sim (dem, |V|, dummyVar) \Rightarrow R^2 = 0.53$ (plot of residuals ok)

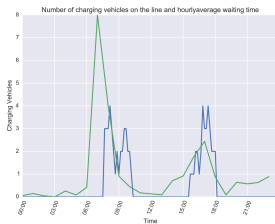
=> $optFleet$ between 6 and 8

We compare the simulation results with 8 vehicles always active and adaptive stopping time at stations without skipping stops.

DYNAMIC FLEET SIZE EXPERIMENTS

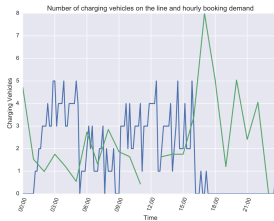
8 Vehicles Active

No dynamic fleet size



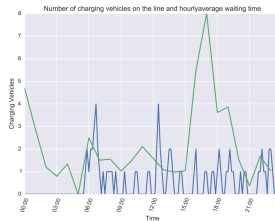
Strategy 1: Cost Function

Fleet size between 3 and 8



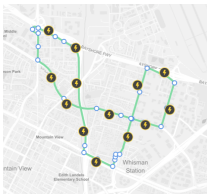
Strategy 2: Max WT 6min

Fleet size between 3 and 8



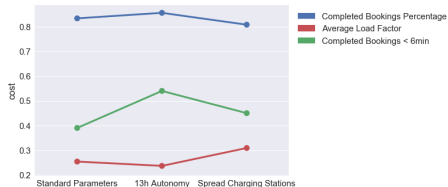
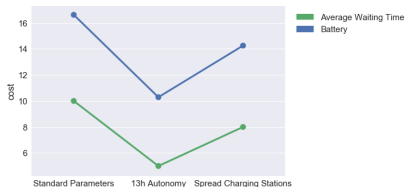
BATTERY MANAGEMENT EXPERIMENTS

Charging Stations' Position



Better Autonomy

Increase battery autonomy from 8 hours to 13 hours



IMPROVEMENT OF PERFORMANCE PARAMETERS BASED ON SCHEDULING STRATEGIES

Difference in percentage to 8 vehicles always active with adaptive stopping times at stations.

Dispatching Strategy	Battery	Waiting Time	Load Factor	Completed Bookings	Completed < 6min
Reference: Constant 8 vehicles	16.61	10	0.25	0.83	0.47
Optional Stops	43	-66	13.26	-3	28
adaptVehicles	-11	-22	19	-5	2
adaptVehicles2	-0.2	-35	55	0	4
Spread Charging Stations	-15	-22	19	-3	17
13h Autonomy	-47	-66	-7	2	29

Thank you!
Questions?